PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 4 : B23K 26/00, B26F 1/31	A1	(11) International Publication Number: WO 86/ 02301 (43) International Publication Date: 24 April 1986 (24.04.86)

(21) International Application Number: PCT/US85/01928

(22) International Filing Date: 4 October 1985 (04.10.85)

(31) Priority Application Number: 661,349

(32) Priority Date: 16 October 1984 (16.10.84)

(33) Priority Country: US

(71) Applicant: ADVANCED LASER SYSTEMS, INC. [US/US]; 223 Crescent Street, Waltham, MA (US).

(72) Inventor: ZAHAYKEVICH, George, Anthony ; 164 Galen Street, Suite 25, Watertown, MA (US).

(74) Agent: KUDIRKA, Paul, E.; Wolf, Greenfield & Sacks, 201 Devonshire Street, Boston, MA 02110 (US).

(81) Designated States: AT (European patent), AU, BE (European patent), BR, CH (European patent), DE (European patent), DK, FR (European patent), GB (European patent), IT (European patent), JP, KP, LU (European patent), NL (European patent), SE (European patent).

Published

With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: LASER DRILLING APPARATUS AND METHOD

(57) Abstract

Apparatus and a method for drilling precision holes in a variety of materials. The apparatus uses a ruby laser to produce a train of light pulses which are focussed by optics onto a workpiece. Each of the pulse in the train can be controlled in peak energy, duration and shape independently from the other pulses in the train and the spot size and shape of each pulse at the workpiece can also be independently controlled. In accordance with the method, a computer operates the laser to drill a small pilot hole in the workpiece using a group of varying pulses. The pilot hole is then widened and reamed with the laser to the final size. On multilayer workpieces, multiple pulses with different pulse width, energy and spatial shape are used at each stage of the hole to prevent workpiece damage, yet allow drilling at reasonable speeds.

LASER DRILLING APPARATUS AND METHOD

This invention relates to apparatus, including lasers, for drilling holes in a variety of materials.

For industrial usage most holes in materials are drilled by mechanically removing material by means of a drill. The drill cuts a spiral chip out of the material to make the hole. However, as the diameter of the hole becomes smaller the hole becomes more difficult to drill. Special drills and backing surfaces must be used to prevent drill "wander" and drilling speeds must be reduced.

The idea of using a laser to drill holes in workpieces became apparent soon after the first lasers were developed. Rather than mechanically removing material to produce a hole, the laser removes material by vaporizing the material or by melting the material and blowing the melted material out of the resulting hole by means of the shock wave which accompanies the laser beam arrival at the workpiece.

The first laser drilling apparatus utilized solid state lasers, generally ruby lasers. The ruby laser has some drawbacks which made it inefficient in normal industrial drilling applications. Specifically, the ruby laser could only be practically operated in a pulsed mode. In addition, the power output of a practical ruby laser system was limited, and thus the system required multiple pulses to drill any but the thinnest materials. Consequently, the drilling rate was slow. However, ruby systems were used to drill small apertures in such materials such as tungsten and molybdenum for use in electron tubes and cathode ray tubes. An

example of such a system is disclosed in U. S. Patent 3,265,855.

Subsequently, gas lasers such as CO_2 lasers were developed, and, due to their ability to produce high power outputs and to operate in a continuous mode, industrial CO_2 gas lasers became very popular for drilling applications.

One problem which soon arose when CO_2 laser drilling apparatus was used to drill various materials was that the various materials had different absorption coefficients of the light generated by the CO_2 laser. In particular, the CO_2 laser was best suited to drilling industrial metals such as steel. However, many other materials which are commonly used in industry were not efficiently drilled by the CO_2 laser because they did not readily absorb the laser light to an extent necessary to vaporize or melt the material. For example, at the output light wavelength produced by the CO_2 laser both copper and gold, which are commonly used in the electronics industry, reflect most of the laser energy. Similarly, ruby crystals, commonly used for watch jewel bearings, were also not efficiently drilled.

Consequently, in order to insure that the necessary amounts of energy were absorbed in the material, a very high-power laser was used and, although most of the energy was reflected, the amount that was absorbed was sufficient to drill the desired hole.

Although the high-power CO_2 laser could drill holes in copper and gold, the necessary power caused additional problems. Typically, a typical laser drilled hole differs from a mechanically drilled hole in that it has a pronounced entrance and exit taper. In addition, the side walls of the laser-drilled hole are often coated with a "recast" layer of material which is formed by liquified material that resolidifies on the walls of a hole. This resolidification process takes place very rapidly and thus the resolidified layer is often of a different composition than the material around the hole which leads to the formation of small cracks in the hole sidewalls. Both the entrance and exit taper and the recast layer are unacceptable in many applications and the high power necessary to drill the holes exacerbated these problems.

When laser drilling apparatus was used to drill holes in materials other than metals, such as electronic printed circuit boards, additional problems arose. Printed circuit boards generally consist of epoxy/fiberglass insulating layers sandwiched between copper or gold metallic conducting layers. As mentioned previously, the high-power CO_2 lasers did not drill the outer metallic layers efficiently and the high-power pulses used caused formation of oxides on the metallic surface and heated the outer layers of the printed circuit board causing them to become delaminated from the underlying epoxy/fiberglass. Also, the high-power pulses often melted some of the epoxy/fiberglass material causing a "smeared"

coating on the hole which prevented subsequent metallic plating of the holes.

Another problem is that the high-power CO_2 lasers required large and bulky power supplies and thus were inconvenient to use.

Other lasers, such as neodynium: yttrium-aluminum-garnet (Nd:YAG) lasers were also developed. These lasers produced a light output which was more suited to drilling materials such as ruby watch jewels, copper and gold, but the output frequency was still not optimal for copper, gold and printed circuit board applications. In order to circumvent the problems with "recast" material and to obtain precise dimensions, Nd:YAG systems which were used to drill watch jewels often used a train of pulses with the energy of the pulses varying from pulse to pulse in the train. Examples of such systems are disclosed in U. S. Patent 3,601,576 (discloses a low energy pulse followed by a succession of higher energy pulses) and U. S. Patent 3,962,558 (discloses a high energy pulse followed by a succession of lower energy pulses).

However, the ruby laser produces a light output which is absorbed more strongly in copper and gold than the light produced by CO_2 or Nd:YAG lasers. In addition, ruby lasers are more suited to drilling sensitive materials due to the "spiky" nature of their output. In a spiky laser, when the laser is operated near threshold, each laser output pulse actually consists of a plurality of very short time duration, high-energy pulses, rather than a long duration medium energy pulse as occurs in a laser

with a non-spiky output. The short time duration pulses tend drill by vaporizing material rather then heating a large area and causing melting.

Consequently, although ruby lasers had fallen into disuse after the development of CO_2 lasers and were generally confined to scientific uses, with the rise of a need to drill small holes in printed circuit boards and copper and gold materials, they were again considered for laser drilling systems.

Ruby laser systems have several inherent problems. In particular, it has been difficult to control the output characteristics of the ruby laser because the ruby crystal is extremely temperature sensitive and is also highly sensitive to the output energy produced by the flashlamp used to excite the ruby crystal. Consequently, prior art ruby drilling systems could not accurately produce consistent pulses and have been limited to drilling materials in one pulse or in a series of pulses of the which generally only the peak energy of the pulse can be controlled. In such prior art systems it has been found that hole size and shape can only be poorly controlled. In addition, prior art ruby laser systems were generally capable of producing only about one pulse per second and, thus, the drilling rates were unacceptably slow.

Even with the use of ruby lasers, problems remained in drilling laminated materials, such as printed circuit boards, with recast layers and smearing of the dielectric layers and with delamination of the boards.

Accordingly, it is an object of the present invention to provide a laser drilling system which can drill properly shaped holes in a variety of materials.

It is another object of the present invention to provide a laser drilling system which can drill laminated materials without causing delamination of the laminated layers.

It is a further object of the present invention to provide a laser drilling system which can accurately drill holes on order of .001 inches.

It is still another object of the present invention to provide a laser drilling system which can drill accurate holes in laminated printed circuit boards without causing delamination of the metal layers or epoxy smear in the hole.

The foregoing problems are solved and the foregoing objects are achieved in one illustrative embodiment of the invention in which a precisely-controlled laser system is operated by a computer to deliver a pre-programmed train of light pulses to a workpiece. The peak power, spot size and pulse spatial shape can be preset for each pulse in the pulse train independently from the other pulses in the train by accurate control of the laser flashlamp supply voltage. Different pulse trains for different materials can be stored in the computer and repeated upon demand.

Because the laser output pulse train can be tailored for each material to be drilled, precise control can be achieved. In particular, a small "pilot hole" can first be drilled through the

material by a number of pulses in a chain. The hole can subsequently be widened to the final diameter by changing the pulse shape of the remaining pulses in the chain. For laminated materials, such as printed circuit boards, a train of low-power pulses can be used to drill through the initial metallic layer. The low pulse power prevents delamination of the metallic layer. After the metallic layer has been pierced, higher-power pulses can be used to drill through the underlying insulating board. Finally, at the far end of the hole, low-power pulses can be used to drill through the opposite metallic layer, again to prevent delamihation.

The hole diameter can be changed by accurately controlling the flashlamp voltage. A change of the flashlamp voltage changes the effective focal length of the optical system due to an effect known as "thermal lensing" of the laser rod. Using this effect, the diameter of the pilot hole can be quickly and easily widened to the final size. Holes with an entrance taper, no entrance taper or an exit taper can also be produced with the inventive system.

Figure 1 shows a front view of the laser drilling system including a T.V. monitor, the computer and the laser head unit.

Figure 2 shows a side view of the illustrative laser drilling apparatus.

Figure 3 is a schematic view of the main system components, including the power supply arrangement and the optical system of the laser drilling apparatus.

Figure 4 is a cross-sectional, cut-away diagram of the laser head.

Figure 5 is a cross-sectional, cut-away diagram of the laser rod support and contoured water jacket.

Figure 6 shows schematically the memory file layout of a laser firing sequence within the computer memory.

Figure 7 is a flow diagram of a sample computer program which is used to control the flashlamp power supply in accordance with the firing information in the computer memory.

Figure 8 is an electrical schematic diagram of the circuit which interfaces the computer to the flashlamp power supply.

Figure 9 is an electrical schematic diagram of the power supply comparator circuit which allows closer control of the power supply voltage.

Figure 10 is a cross-sectional view of the workpiece drilled in accordance with Example 1 herein.

Figure 11 is a cross-sectional view of the workpiece drilled in accordance with Example 2 herein.

The general layout of a practical drilling arrangement in accordance with the present invention is shown in Figure 1. The drilling apparatus consists of a cabinet 1, which is approximately the size of an ordinary office desk. The cabinet houses a power supply 2 on its left side and a refrigerant cooling system 3 on its right side.

Mounted in the center of the cabinet is the laser and optic stand 4. To the right of stand 4 is a computer 13 which is used to control the apparatus, and to the left of stand 4 is a T.V. monitor 10 which is used to monitor the progress of the drilling.

The exact computer which can be used with the system is not important for operation of the inventive drilling system. In the preferred embodiment, a Model II+ personal computer manufactured by Apple Computer, Incorporated, Cupertino, California, is used. Similarly, personal computers manufactured by the International Business Machines Corporation, Armonk, New York, or other manufacturers can be used.

The laser and optical stand 4 is arranged with the laser 5 mounted horizontally on the top and stand 4 has an optical bench 6 arranged vertically down its front face. The optical bench 6 contains two lenses 7 and 9 and a pinhole 8 which are arranged in series, as will be described hereinafter in more detail.

Also mounted on optical stand 4, is a T.V. camera 11 which is connected, via cable 12, to monitor 10. Camera 11 is focussed on workpiece 14 and can be used to monitor workpiece 14 after each series of laser pulses.

As with the computer, the exact model of the television monitor and camera is not important to the operation of the invention as long as the camera and monitor have sufficient resolution to satisfactorily observe the progress of the

drilling. In the preferred embodiment a Model 5000 high-resolution camera and monitor system manufactured by COHU, Inc. San Diego, CA, are used. Instead of a mechanical shutter, a filter on the camera lens is used to permit the camera to be kept on at all times.

Figure 2 is a side view of the laser drilling apparatus showing the cooling system control panel 20. Also shown in more detail is the optical stand 4. Mounted on the optical stand 4 is a laser assembly 5, consisting of a ruby rod and its cooling jacket 34 and a flashlamp and its cooling jacket 36. Both rod 34 and flashlamp 36 are enclosed in a reflector 35. Two mirrors 32 and 33 are mounted on either side of rod 34 to produce a conventional laser cavity. Alternatively, mirrors 32 and 33 could actually be part of the rod itself in a conventional fashion. The front portion 30 of the laser platform is bent at a 45-degree angle and has a mirror 31 affixed to its inside face. The beam developed by rod 34 is reflected from mirror 31 and is directed downward through the optical bench to the workpiece 14.

Also, shown in more detail in Figure 2 are the imaging lenses 7 and 9 and the pinhole 8 which are used to form the laser drilling beam as described below.

In order to produce satisfactory results in drilling materials using the inventive pulse train and thermal lensing techniques, it is necessary to control the laser output so that each separate laser pulse with a particular energy, spot size spatial

shape can be reproduced within a 1% variation of another pulse of the same energy, duration and shape. In prior art systems this tight control has not been possible for a variety of reasons. In particular, it has been difficult to control the characteristics of the ruby laser because the ruby material is extremely sensitive to temperature and flashlamp output energy.

According to the present invention, in order to control the temperature characteristics of the ruby laser and to allow a drilling rate of 3-5 pulses per second, a conventional refrigerated cooling system is used. As a cooling medium, the system uses distilled, de-ionized water which is circulated by a circulator pump through cooling jackets surrounding the ruby rod and flashlamp. The flow rate of the water is adjusted to about four gallons per minute at 15 P.S.I.

The cooling water is in turn chilled by a conventional refrigerant system. The cold refrigerant liquid removes heat from the water by means of a heat exchanger which is a conventional unit made from copper using a tube-in-tube design. In order to achieve precise temperature control, the refrigerant system is controlled electronically. The electronic control utilizes a platinum sensor to activate a controller which, in turn, operates a valve to control the flow of refrigerant to the heat exchanger. Use of the electronic control eliminates compressor cycling and provides a very quick response, in turn, giving good accuracy and stability. Temperature regulation can also be

improved using conventional computer monitoring techniques. Using well-known conventional refrigeration techniques, a temperature control accuracy on the order of ± 0.1 degrees Centigrade at the laser head can be reliably achieved.

Also in accordance with the invention, in order to insure uniform cooling of the laser rod, the design of the cooling water jacket is important. In a ruby laser, cooling is normally a problem because the ruby rod has a relatively low coefficient of thermal conductivity at normal ambient temperatures. In addition, the coefficient of thermal conductivity changes with rod temperature. Thus, in high-power output situations, the rod can become unevenly heated resulting in stresses and eventual failure.

Accordingly, an efficient cooling system must uniformly cool the entire rod. Generally, it is useful to keep the rod as cool as possible because at lower temperatures the coefficient of thermal conductivity of the ruby increases. In the present invention, the cooling system is designed to keep the rod at 40 degrees Centigrade ± 0.1 degree Centigrade. In order to reliably hold the rod at this temperature, coolant is pumped directly over the rod by means of a glass cooling jacket. The glass cooling jacket which surrounds the rod must be specially contoured to prevent uneven cooling, as will hereinafter be explained in detail in connection with Figure 4.

Another problem with prior art laser systems is that they cannot precisely control the laser output energy because the exciting flashlamp firing voltage

cannot be controlled accurately. It is known that the output power of a laser pulse in a ruby system is extremely dependent on the output intensity of the flashlamp. The output intensity of the flashlamp is, in turn, directly dependent on the voltage applied to the lamp to flash it.

The conventional way of firing a laser pumping flashlamp is to utilize a high-voltage D.C. supply to charge a large capacitor. After the capacitor is fully charged the power supply is disconnected and, when it is desired to flash the lamp, electronic switches are closed to connect the charged capacitor across the flashlamp which, in turn, causes the energy in the capacitor to be released into the lamp. However, with this conventional arrangement there is typically a "drift" or change in the voltage on the charged capacitor due to leakage during the "holding" time interval between the charging of the capacitor and the actual firing of the flashlamp. Although the time interval between the charging and the firing of the lamp may be only a few milliseconds, a conventional power supply/capacitor firing arrangement can only regulate the voltage applied to the flashlamp to within 5% of the desired value on each lamp firing.

Prior art methods are known which can reduce this voltage variation. In particular, some conventional power supplies have internal circuitry which recharges the charge storage capacitor during the holding time between the charging and the firing. These power supplies typically repetitively generate a desired firing voltage with only a 1%

voltage variation. An example of such an improved power supply/ capacitor system is a Model HVD-5000, 5-killijoule power supply manufactured by the Candella Corporation, Natick, MA. However, in accordance with the present invention, even this power supply must be specially controlled to bring the final voltage variation in the range of 0.1% to 0.05%. This special control is carried out by a comparator circuit which monitors the output voltage and continually recharges the firing capacitors, as will be hereinafter described.

Another source of variation in prior art laser systems is the flashlamp itself. In accordance with normal practice, one method of firing the flashlamp after charging of the energy storage capacitor is by connecting a high voltage source momentarily across the flashlamp electrodes. The high-voltage produces a low-current, highly-ionized stream between the flashlamp electrodes. Subsequently, the full charge stored in the capacitor passes through the lamp over the same path as the initial stream. Such a firing arrangement gives an approximately 5% accuracy in firing because the initial low-current ionized stream follows an essentially random path, often running down the glass walls of the flashlamp. Not only does this random firing path cause a variation in the main discharge path length, but it can also rapidly deteriorate the lamp if the main discharge repeatedly occurs on the glass wall of the lamp.

Accordingly, better results can be obtained by using a "simmer" supply which is a known unit used for flashlamps. In the preferred embodiment a

combination simmer supply and dump switch unit Model FD-100 supply manufactured by the Candella corporation is such a simmer supply. In a simmer supply arrangement, prior to charging the energy storage capacitors or firing the lamp, an initial high-voltage is placed across the lamp electrodes to establish a "streamer" of ionized gas which travels down the center of the lamp. A low-current trickle charge then maintains the streamer continuously, even when the lamp is not actively flashing. When the lamp is to be flashed, large power diodes are used to switch the main charge onto the lamp electrodes which charge then follows the pre-established streamer path.

The simmer operation insures that the discharge will not occur on the wall of the lamp, thereby prolonging the flashlamp life. In addition, since the discharge always occurs in the center of the lamp, the pathlength is known and predictable resulting in less variation on each firing. It is also easier to align the flashlamp with the laser rod in a reflector housing to get improved accuracy.

Figure 3 of the drawing shows a schematic view of the illustrative system including the power supply arrangement and the optical system. The ruby laser rod is schematically shown as rod 34. Rod 34 is excited by a xenon flashlamp 36 which is fired by the power supply consisting of high voltage power supply 2, simmer supply and dump switch 51, capacitor 50 and choke coil 52. A flashlamp suitable for use with the preferred embodiment is a Model FX-227C-6 flashlamp manufactured by EG&G Incorporated, Waltham, Massachusetts.

Power supply 2 is a conventional design which is capable of charging capacitor 50 to a voltage of between 0 and 2500 VDC. The voltage to which the capacitor is charged is controlled by the value of the voltage input V_{ref} provided to supply 2 by the interface circuit 40. Interface circuit 40 also provides other signals to power supply 2 which control supply 2 and allow it or prevent it from charging capacitor 50. These signals are schematically shown as charge inhibit signals on Figure 3 and will be described in more detail hereinafter.

Supply 2 coordinates with the simmer supply and dump switch unit 51 by means of interlock signals which are passed between the units. Dump switch 51, in turn, fires flashlamp 36 by connecting capacitor 50 to choke coil 52 under control of a trigger signal developed by the interface circuit 40. The trigger signal is also provided to the power supply 2 to prevent it from attempting to charge capacitor 50 while the flashlamp 36 is being fired. Choke coil 52 delivers a shaped charge pulse to lamp 36 to fire it.

Power supply 2 internally contains a comparator which continuously compares the output voltage to the desired voltage (as determined by the value of V_{ref}) to indicate when the output voltage is equal to the desired voltage. In particular, the output of the comparator is provided as signal V_{rdy}* to interface circuit 40. Signal V_{rdy}* becomes "low" when the output voltage is equal to the desired voltage, and, as will hereinafter be described, this

latter signal is used by interface circuit 40 to generate a trigger signal which is provided to dump switch 50 to, in turn, flash lamp 36.

Power supply 2 also contains internal circuitry (discussed in detail in connection with Figure 9) which continuously recharges capacitor 50 to compensate for any voltage drift between the time when the capacitor is fully charged and the lamp firing time. This recharging circuitry also operates from the internal comparator so that the power supply output is always close to the desired value when interface circuit 40 fires the lamp. This close control helps to achieve accurate control of the laser output pulses.

Supply 2, in turn, receives programming commands, via interface circuit 40, from computer 13. As will be described hereinafter in detail, interface circuit 40 receives a digital command word from computer 13. The value of this word is converted into an analog voltage which is provided as the control voltage V_{ref} to power supply 2. Interface circuit 40 also interacts with computer 13 by means of a status word and handshake signals to insure proper coordination of the firing sequences, to introduce proper timing delays and to insure safety for those operating the system.

Computer 13 can be programmed to store a series of data files each of which programs supply 2 to produce a train of predetermined voltages. When these voltages are applied to lamp 36, it excites laser rod 34 to produce output pulses with predetermined shapes, intensities and energies.

The output beam 45 of laser rod 34 is passed through a conventional condensing lens 7 and impinges on pinhole 8. Pinhole 8 blocks the marginal light rays and creates a waist 46 in the beam. The diameter of pinhole 8 depends on the exact lens arrangement and the physical distances involved. In the illustrative embodiment, pinhole 8 has a diameter approximately 2-3 times the desired spot size on the workpiece. In the illustrative embodiment, the diameter of pinhole 8 is .020 inch. In accordance with the conventional theory of coherent light optics, the pinhole 8 acts as a new light source. The light from this source (beam 47) is directed to an additional condensing lens 9 which focuses the beam on workpiece 14 at spot 48.

Figure 4 shows a detailed sectional diagram of laser head 5 of the illustrative drilling apparatus. Laser head 5 is of conventional design consisting of a flash lamp 36 and ruby crystal rod 34 closed in elliptical reflector 35. In the illustrative embodiment, rod 34 is a 0.25 inch diameter by 6 inch long C-axis ruby crystal of the highest commercial quality.

The elliptical reflector structure 35 which encloses both rod 34 and flashlamp 36 is an brass reflector with a silvered inner surface, as is conventional. In order to insure maximum power output, both the rod and the flashlamp must be precisely located at the foci of the ellipitical reflector.

The elliptical pump cavity is completed by end reflectors 58 and 59 which are reflecting surfaces. Surfaces 58 and 59 are backed by end plates 61 and 63, respectively. Located inside the reflecting surfaces 58 and 59 are forming plates 56 and 57 which are used to hold the brass sheet 35 in an elliptical shape.

The laser cavity is formed by mirrors 32 and 33 which are connected to stands 170 and 172 by means of adjusting nuts 110 and 112 respectively. The adjusting nuts allow the mirrors to be adjusted so that they are perpendicular to the laser beam. The laser beam 45 exits by the right hand side of the unit and is reflected from front-silvered mirror 31 in a downward direction the workpiece (not shown). In order to prevent damage by the laser beam the mirrors must be highly reflecting on the order of 99.999% reflectivity at the operating optical frequency.

Both laser rod 34 and flashlamp 36 are enclosed by cooling jackets to permit water cooling of the units as previously described. In particular, rod 34 is enclosed by quartz jacket 80. This jacket should be transparent to all optical frequencies of interest. In order to provide for proper cooling ends 82 and 84 and jacket 80 are contoured to ensure uniform water flow over the ends of the rod and the holding structures. The water jacket is completed by water inlet/rod holder fittings 60 and 62. In operation, cooling water enters the assembly by means of inlet pipe 66 and leaves the assembly by means of pipe 64.

The ends of the rod assembly are fitted with nitrogen purge fittings 66 and 68 which allow the ends of the rod to be surrounded with dry nitrogen gas, via fittings 70 and 72, respectfully. The inside of the reflector chamber is also purged with dry nitrogen. The use of dry nitrogen gas permits the rod to be operated at chilled temperatures without the formation of condensation on the ends of the rod or on the cooling water jacket which would reduce the power output.

A more detailed sectional view of the laser rod end as shown in Figure 5. Rod 34 is fixed in rod holder fitting 100. A seal is made around the periphery of the rod at its end by O-ring 92 which is, in turn, compressed by compressor fitting 102. O-ring 92 prevents coolant leakage around the end of the rod into the cavity 101.

In accordance with the invention, the end of rod 34 is restrained only by friction of O-ring 92. Thus, the rod is free to move due to thermal stresses. In particular, the shape of the rod changes during the firing of a laser pulse due to a phenomenon known as "thermal lensing". Such a phenomenon is well-known in the art and is described in detail, for example, in <u>Solid State Laser Engineering</u> by W. Koechner, published by Springer-Verlag, New york, 1976, Section 7.1.2, pages 365-382. In the present system, the effect of thermal lensing is to change both the shape of the output pulse at the workpiece and the effective focal length of the laser system. Normally, such a thermal effect is undesirable because it is

generally non-repeatable. However, in the present system, with precise control of the flashlamp voltage and cooling, the thermal lensing effect is repeatable and can be used with advantage to change the shape and pulse width of the laser pulse as well as the effective focal length of the system in order to drill optimally certain materials.

Rod holder fitting 100 is, in turn, sealed to the inlet fitting 62 by means of O-ring 94. The coolant (water) enters the structure via inlet pipe 66 and proceeds down space 83 between water jacket 80 and rod 34 to cool the rod. As previously mentioned, in order to insure uniform cooling, the end 82 of jacket 80 is contoured to match the slope of rod holder 100. This contouring ensures a uniform flow velocity over the ends of the rod and ensures that no eddies are formed which would cause uneven rod heating and imprecise performance. Inlet fitting 62 is attached to endplate 63 by means of screws (not shown) in order to mount the the rod holder assembly in the end plate.

Attached to the end of O-ring compressor fitting 102 is purge fitting 68 which has a transparent window 69. As previously mentioned, fitting 68 allows cavity 101 to be purged with dry nitrogen via pipe 72.

Referring again to Figure 4, flashlamp 36 is also surrounded by a glass water jacket 150. In operation, cooling water enters jacket 150 by means of tube 128, flows around electrode 120, down jacket 150, around electrode 122 and exits via pipe 130. In the illustrative arrangement, pipe 130 is

connected to inlet fitting 66 so that water flows around flashlamp 36 then through jacket 80 around rod 34 and exits via fitting 64. To prevent distruction of the silvered cavity reflector the cooling jacket should be highly absorptive of ultraviolet optical frequencies emitted by the lamp. Suitable materials include antiultraviolet quartz or pyrex.

Power to lamp 36 is provided by electrodes 120 and 122 which are connected to the high voltage power supply (not shown in Figure 4) via leads 124 and 126, respectively.

As previously described, the inventive laser drilling system is controlled by a computer. The computer can controls the power supply voltage provided to the flashlamp in precise 5-volt steps for each shot fired and the computer is capable of firing a pre-programmed sequence of shots with any given voltage. This sequence of shots can be pre-programmed for each particular material to be drilled providing for optimum drilling speed and hole shape for each material.

Figure 6 of the drawing shows the organization of the control data base structure within the computer memory which stores the information that is used to control the laser system for each output pulse sequence. In particular, the database is arranged in a plurality of data "files". Each of the files contains information regarding a set of power supply voltages which are used to develop a particular pre-programmed series of laser pulses or "shots".

A number of files can be stored in a storage device, such as a magnetic disk or tape, and recalled in any sequence to generate various output pulse patterns. The information in each file is organized in an "array" or matrix which consists of N+1 rows by 4 columns. Each row and column location in the array consists of an address in memory at which is stored information that is used by the computer program to control the power supply to generate a predetermined voltage.

In particular, the first row of the array contains general information which is used by the computer to initialize the program by setting limit registers and parameters. Each of the remaining array rows contains information which is used by the program to develop and sequence flashlamp firing voltages for a discrete set or "group" of output pulses. Each pulse group developed by the system consists of a predetermined number of laser pulses each generated by the same predetermined flashlamp voltage.

More specifically, information stored in the first location, 600, indicates the total number of groups in the file. Location 650 at row 1, column 2, contains a number representing the total number of laser pulses or shots which will be fired for the entire file. The total shot number is used to set an internal counter which then compares the total number of shots actually fired with the total number stored in the array so that the computer can determine that all laser shots have been fired and that the file has been completely processed.

Location 652 in the third column contains information indicating the types of lasers which are to be controlled by the information in the array. In particular, although in the preferred embodiment, only a ruby laser is used for drilling purposes, the same computer system may be used to sequentially control several different types such as one or more ruby lasers, Nd:YAG lasers or CO_2 lasers. Location 654 is not used.

Each of the remaining rows consists of information relating to a particular group of shots to be fired. The information is arranged in the same manner for each group. In particular, the first location in column one (for example, location 601) contains information indicating the number of shots to be fired during processing of that particular group. The information in the second column (for example, location 656) indicates the type of laser which is to be used for firing shots in that group.

The information in the third column (for example, location 658) contains numerical information which indicates the "raw" or unrounded flashlamp voltage which is to be used to fire each of the shots in the group.

The fourth location for each group contains a code word which is a binary approximation of the raw voltage (expressed in decimal volts) to be applied to the power supply. The code word is actually applied to the interface circuitry which (as will hereinafter be described) controls the flashlamp power supply. Due to rounding errors, and an

inexact conversion between binary and decimal mathematics the code word represents a voltage which may not be exactly equivalent to the "raw" voltage information stored in location 658. In particular, the code word is related to the raw voltage by the following equation:

B = INT((A-700)/5.078 + 0.5)

where B is the code code word that is stored in location 660, A is the raw voltage stored in location 658 and INT () is an integer function which selects the integer portion of the variable enclosed in parentheses. The addition of 0.5 in the above equation causes the volts to be the nearest binary code to the raw voltage withing a $\pm$ 2.5 volt tolerance.

A file such as that shown in Figure 6 may be set up by standard file manipulation routines and the information consisting of the group information may be entered, changed or deleted by means of standard data manipulation routines. Since the operation and programming of such file and data routines is well-known, it will not be described in detail herein.

Once a file such as that shown in figure 6 has been established, a simple program or routine can be used to send the stored data to the interface circuitry to control the flashlamp power supply which, in turn, controls the laser output. Such a routine is shown in flowchart form in Figure 7.

Referring to Figure 7, the file output routine starts with step 702. In step 704, the routine loads an internal register with the total number of groups. For a particular file, this number is obtained from the file array location at row 1, column 1.

In step 706, the count of a group counter set is equal to zero. In step 708, the count of the group counter is compared to the total number of groups which were stored in the internal register in step 704 to determine whether all groups have been processed.

Assuming that the numbers are unequal and that some groups remain to be processed, the routine proceeds to step 710, in which the group counter is incremented. In step 712, the routine then loads the total number of shots for the group (with a group number equal to the count in the group counter) obtained from the first file array column of the file array row corresponding to the group number.

In step 714, the routine sets a shot counter equal to zero. In step 710, the routine compares the count of the shot count to the total number of shots loaded in step 712 to determine if any shots remain to be fired.

Assuming that these latter two numbers are not equal and that additional shots remain to be fired, in step 718, the routine increments the shot counter and proceeds to step 720.

In step 720, the routine checks to see if the first shot is being fired (if so, the shot counter will be equal to one). If the shot being fired is the first shot, then the routine skips to step 726 in which the code word indicating the voltage to be used for the firing is sent to an output port which is connected to the interface circuit. This voltage code word is the code word stored in the memory location corresponding to column 4 for the group row being processed.

After the code word has been sent to the output port, in step 728, a DATA STROBE* ("*" following a signal indicates that it is active in its "low" state) signal is generated at another output port which signal (as will hereinafter be described) causes the interface circuitry to process the code word and set the charging voltage of the flashlamp power supply to the correct level.

In step 730, the routine then loads a status word appearing at the computer's input port into an internal register and, in step 732, checks a status word to determine whether the requested shot has, in fact, been fired by the interface circuitry. If not, the routine continues polling the status word by repeating steps 730 and 732. If the status word indicates that the shot has been fired, the routine turns to step 716 in which the count of the shot counter is compared to the total number of shots to see whether all shots have been fired. If shots remain to be fired, the routine repeats steps 718-732.

Returning to step 720, if the shot to be fired is not the first shot, then the routine proceeds to step 722 in which a status word is loaded. This status word consist of signals developed by the interface circuitry which indicate whether the firing system is charging or is in the process for firing a shot as commanded. In step 724, the status word is checked to make sure the system is ready to accept new voltage data.

If the status word indicates that the system has finished firing the preceding shot, the routine proceeds to step 726, in which the new voltage code information is sent to the output port. Subsequently, the DATA STROBE* signal is sent (step 728) and the routine proceeds as previously described. If, in step 724, the status word indicates that the system is not ready to accept new data, the routine waits by repeating steps 722 and 724 until proper status is achieved.

Operation continues in the previously-described manner until, in step 716, the shot counter equals the total number of shots for the group indicating all the shots for the group have been fired. In this case, the routine proceeds to step 734 in which an ENDGROUP* signal is sent to the interface circuit which disables the power supply charging circuitry, as will hereinafter be described.

The routine subsequently proceeds to step 708 where the count in the group counter is compared to the total number of groups. If there remain groups to be processed (as indicated by an inequality in the two numbers) a new group shot count is loaded

and the shot routine, consisting of steps 710-732, is repeated.

Alternatively, if the count in the group counter is equal to the total number of groups, the entire file has been completed and the routine then proceeds to end, step 736. At this point another file may be loaded and fired in the same manner.

Referring to Figure 8, an electrical schematic diagram of the interface circuitry which accepts data and control information from the computer and converts it into analog signals to control the power supply is shown in detail.

The interface circuit connects with the computer via the terminals shown at the left-hand side of Figure 8. In particular, the interface circuitry receives code word voltage signals from the computer via data bus 800. In addition, the interface circuitry receives a DATA STROBE* signal, via terminal 816, which signal is a negative-going signal indicating that the data on the data bus 800 is valid.

An ENDGROUP* signal is provided from the computer to the interface circuit on terminal 817. The ENDGROUP* signal is a negative-going pulse indicating that all of the shots in a group have been fired.

In addition to receiving information from the computer, the interface circuitry also sends to the computer status signals, via terminal 818, which signals are sent to the computer's input bus.

The interface circuit also connects to the high voltage flashlamp power supply via the terminal shown at the right-hand side of Figure 8. In particular, the interface circuit provides the power supply with a voltage reference signal (V_{ref}) via terminal 810 and charging inhibit signals (R-INHIBIT and C-INHIBIT) via terminals 811 and 813. The latter charging control signals act in parallel to control the flashlamp power supply to prevent or allow charging. In order for the supply to begin charging, both the R-INHIBIT and the C-INHIBIT signals must be low. When charging is allowed, the supply automatically charges to a voltage specified by the V_{ref} signal at terminal 810.

After the power supply has charged to the commanded voltage level, it returns a signal (V_{rdy}*), via terminal 819, which signal indicates that the proper charging voltage has been reached (the V_{rdy}* signal becomes "low" when the proper voltage has been reached).

In response to the V_{rdy}* signal, the interface board provides a TRIGGER* signal on terminal 815 to the dump switch which signal causes charge stored in the capacitor to be passed through the flashlamp and a similtaneously charging disable signal, C-INHIBIT.

Specifically, binary signals on data bus 800 indicating the firing voltage to be placed on the flashlamp are provided via bus 802 to digital/analog converter 804. Although bus 802 is shown only as a heavy line, it, in fact, consists of eight separate leads.

Digital/analog converter 804 is a well-known device which converts a binary signal at its input terminals to an analog output signal. The output signal of converter 804 is provided to the positive input of a differential subtracting instrumentation amplifier 806. Amplifier 806 is a well-known type of amplifier circuit made of two or more operational amplifiers. The subtracting input of amplifier 806 receivesa signal 808 which is developed by precision inverter 812. Precision inverter 812 inverts a precision reference voltage supply 814 to generate the negative reference signal 808 which undergoes a sign reversal and is summed as a fixed voltage or offset turn whith the output of converter 804 inside amplifier 806 to generate output 810. Amplifier 806, processes the converter output signal to adjust its gain and offset so that the converter output signal will be at the proper level for application of the power supply which accepts a 0-6 volt input signal with a transfer function that yields an output of 0-2500 volts.

Specifically, the output of amplifier 806 is provided to terminal 810 and from there to the flashlamp power supply. In accordance with the invention, it is important that amplifier 806 and reference inverter 812 are precision devices compensated for both temperature drift and noise so that the output voltage on terminal 810 will be consistent for the same data input. In the illustrative embodiment, the gain of amplifier 806 is adjusted so that the output voltage on terminal 810 varies between 1.57 volts to 5.91 volts. With

the particular power supply used in the preferred embodiment, such a voltage range causes the output charging voltage to range between 700 and 2500 volts.

As previously mentioned, after the computer places a voltage control word on data bus 800, it places a negative-going data strobe signal on terminal 816. This latter signal initiates a chain of events which allows the power supply to begin charging.

In particular, the "low" DATA STROBE* signal on terminal 816 is supplied to the set inputs of DATA flip/flop 824 and RESET flip/flop 826. These inputs are normally held "high" by means of resistor 822 which is connected to voltage supply 820 and the negative-going DATA STROBE* signal sets both flip/flops.

When DATA flipflop 824 is set, it produces a "low" signal at its Q* output which "low" signal is supplied to the reset input of INHIBIT flip/flop 828. Flip/flop 828 is thereupon reset causing a "low" signal to appear at its Q output, which "low" signal, in turn, is applied to buffer/driver 830. In response to a "low" signal at its input, buffer/driver 830 applies a "low" signal to the coil 831 of relay K4. The other lead of coil 831 is connected to positive voltage source 832. Relay K4 thereupon operates. Operated relay K4 opens contact 834 and closes contact 836. Relay K4 remains in this state until the last ENDGROUP* signal of the computer control sequence executes and the TIMEOUT signal ends, as described hereinafter.

When contact 834 opens, resistor 840 places a "low" signal on the R-INHIBIT terminal, 811. This signal allows the power supply to begin charging. In addition, when contact 836 closes, it connects voltage source 832 to light-emitting diode (LED) 838, causing it to glow. The glow of LED 836 indicates that the power supply is conditioned to charge.

However, the power supply cannot begin charging until a "low" signal is provided to the C-INHIBIT terminal 813. Such a "low" signal is provided when the "low" signal on the Q* output of set flip/flop 824 is provided to the upper input of OR gate 842. The lower input of gate 842 is connected to the output of the TIMEOUT single-shot multivibrator 844. At this time the output of multivibrator 844 is "low". Accordingly, OR gate 842, having "low" signals at both its inputs, produces a "low" signal at its output which "low" signal is applied to the C-INHIBIT terminal, 813.

With "low" signals on both the R-INHIBIT terminal 811 and the C-INHIBIT terminal 813, the flashlamp power supply begins charging the storage capacitor to a voltage specified by the V_{ref} signal on terminal 810.

As previously mentioned, the power supply contains an internal comparator so that, when its output voltage reaches the proper voltage, a "low" signal is applied by the comparator as the $V_{rdy}*$ signal on terminal 819. The power supply circuitry is arranged so that if the power supply discharges between the time that the voltage reaches its proper

level and the time when a trigger signal is generated, internal circuitry recharges the storage capacitor to the proper level. During such a recharging operation the V_{rdy}* becomes "high". After the recharging operation is complete, the V_{rdy}* signal again becomes "low".

A "low" V_{rdy}* signal is provided to signal conditioning circuit 846 which provides voltage level-shifting to shift the V_{rdy}* signal to the proper voltage levels required by the integrated circuitry in the interface board and also filters out noise. Circuit 846 may illustratively consist of transistor level-shifting circuits followed by a single-shot multivibrator. The design of such circuits is well-known and will not be described in detail herein.

The output of signal conditioning circuit 846 is a negative-going pulse which is applied to the trigger inputs of TIMEOUT single-shot multivibrator 844 and TRIGGER single-shot multivibrator 848. These trigger inputs are normally held "high" by resistor 850 and voltage source 852 and the negative-going signal activates the devices.

TIMEOUT single-shot multivibrator 844 is a well-known circuit device which may consist of a 555 integrated circuit of one-half of a 556 integrated circuit connected to appropriate capacitors and resistors. When device 844 receives a "low" signal at its trigger input, it produces a "high" TIMEOUT signal at its output lead, which "high" signal is adjustable to last between approximately 25 milliseconds to 2.5 seconds. The "high" signal

provides a timed interval during which firing of the flashlamp takes place. Among other things, the TIMEOUT signal is used to disable charging of the power supply during the firing interval and to prevent the setting of the INHIBIT flip/flop 828 (discussed above) until the computer control sequence has time to initiate a new action such as an additional shot.

In particular, the "high" signal at the output of multivibrator 844 is applied to the lower input of OR gate 842 causing it, in turn, to apply a "high" signal to the C-INHIBIT output terminal, 813. As previously mentioned, a "high" signal on terminal 813 prevents the flashlamp power supply from charging.

The "high" output of the TIMEOUT single-shot multivibrator 844 is also applied to the TIMEOUT status lead which is provided to the computer, indicating that the interface circuit is in a TIMEOUT period.

In addition to stopping the charging of the power supply the V_{rdy}* signal also initiates the firing of the flashlamp. In particular, the "low" output of signal conditioning circuit 846 which, as previously mentioned, is generated by the V_{rdy}* signal, is also applied to the trigger input of TRIGGER single-shot multivibrator 848. Multivibrator 848, in response to the rising edge of a signal applied to its trigger input, produces a "high" TRIGGER signal which lasts for about 2 milliseconds. This "high" TRIGGER signal is provided to trigger pulse generator 868. Trigger

pulse generator 868 is also a single-shot multivibrator which differs from single-shot multivibrators 844 and 848 in that it is triggered by a rising-edge appearing at its trigger input.

Consequently, when the "high" TRIGGER signal generated by TRIGGER multivibrator 848 appears at the input of multivibrator 868, it generates an output pulse. This pulse has a duration of about 12 microseconds and is provided as a TRIGGER signal, via level shifter 847 and terminal 815, to the simer supply and dump switch and the high voltage supply. Level shifter 847 converts to 0-35 volts pulse produced by multivibrator 868 to a 0-8 volts signal utilized by the power supply. The TRIGGER signal causes the dump switch to "dump" the charge stored in the storage capacitor into the flashlamp causing the flashlamp to fire. The trigger signals also inhibits the supply from charging during flashlamps firing as will be hereinafter described.

The "high" output of the TRIGGER single-shot multivibrator 848 is also used to generate a signal to the computer to indicate that a shot has been fired. Specifically, the "high" output of the TRIGGER single-shot multivibrator is applied to the trigger input of ACKNOWLEDGE single-shot multivibrator 870. This multivibrator is similar to trigger pulse generator 848 in that it responds to a negative-going signal at its input. Accordingly, the ACKNOWLEDGE single-shot multivibrator produces a "high" DATA ACKNOWLEDGE* signal of a duration of approximately 2 milliseconds at its output.

When this "high" signal becomes "low," it pulls the left-hand lead of capacitor 872 low (the left-hand lead of capacitor 872 is normally held "high" by resistor 874 and voltage source 876). Capacitor 872 acts as a voltage differentiator and, accordingly, places a negative-going pulse on lead 878. This negative-going pulse is, in turn, applied to the reset input of DATA flip/flop 824, resetting it.

Flip/flop 824, when reset, generates signals that indicate to the computer that the laser has been fired. In particular, a "low" signal on the Q output of DATA flip/flop 824 is provided to the computer via the DATA RDY status terminal. The computer is also informed that firing of the laser has been started because the pulse generated by the DATA ACKNOWLEDGE multivibrator 872 is connected to the DATA ACKNOWLEDGE terminal of status terminals 818.

As previously mentioned, after all shots in a particular group have been fired, the computer places a negative-going ENDGROUP* signal on terminal 817. The function of this pulse is to cause the interface circuit to place a "high" signal on the R-INHIBIT terminal to prevent the power supply from charging for personnel safety reasons. However, in order to prevent premature inhibition of the power supply, logic circuitry is provided to prevent the R-INHIBIT terminal from being raised until the firing sequence for all pulses is complete (as noted above in the discussion concerning relay K4).

More specifically, the negative-going ENDGROUP* signal is applied to the reset input of RESET flip/flop 826, in turn, resetting the flip/flop and causing it to apply a "low" signal to its Q output. This "low" signal is applied to the RESET status terminal indicating to the computer that the interface circuit has been reset. The "low" signal is also applied to the left-hand lead of OR gate 862.

Assuming that all firing activity has been completed as described below, the output of OR gate 860 will be "low". Thus, OR gate 862 will receive "low" signals at both its inputs. Accordingly, OR gate 862 places a "low" signal on its output which is applied the voltage differentiator consisting of capacitor 864 and resistor 866. This differentiator causes a negative-going pulse to be provided to the set input of INHIBIT flip/flop 828.

In response to a negative-going signal at its input, INHIBIT flip/flop 828 becomes set, and places a "high" signal on its output Q. This "high" signal is, in turn, provided, via buffer driver 830, to the coil 831 of relay K4. Since relay coil 831 now has a "high" signal in both of its leads, it releases. When released, relay K4 opens contact 836 and closes contact 834.

When contact 836 opens, LED 838 is no longer connected to voltage source 832 and therefore is extinguished. Voltage source 832 is now connected, via closed contact 834, to the R-INHIBIT terminal 811. The "high" signal on the R-INHIBIT terminal 811 prevents the power supply from charging.

However, if the firing sequence is not completed when the RESET flip/flop is reset as described above, then the INHIBIT flip/flop will not be set because OR gate 862 will receive a "high" signal at its right-hand input from OR gate 860. In particular, OR gate 860 indicates when there is activity during the firing cycle, that is, when the power supply is waiting to be triggered or when the power supply has been triggered to fire the flashlamp. Since the output of gate 860 holds the output of gate 862 "high" during such activity, the INHIBIT flip/flop 828 cannot be set.

OR gate 860 monitors the status of the TIMEOUT multivibrator and the TRIGGER multivibrator. The TIMEOUT signal, as previously described, is "high" when a V_{rdy}* signal has been received from the power supply indicating that the capacitor has been charged to the commended voltage. The output of the TRIGGER single-shot multivibrator is "high" when the triggering of the power supply is in progress.

Figure 9 of the drawing is a schematic diagram of a portion of the electrical circuitry of the high-voltage power supply. This circuitry includes a comparator circuit which allows the power supply to recharge the energy storage capacitors during the time interval between the initial charging of the capacitor and the firing of the flashlamp. As previous mentioned, this recharging capability allows the power supply to maintain a constant charge voltage on the energy storage capacitors to within approximately 1% of the programmed value. This close voltage control is necessary in order to

allow repeatable results when firing a sequence of pulses in accordance with the invention.

More particularly, the reference voltage, V_{ref}, (which, as previously described, is the control voltage that is developed by the interface circuity and determines the value of the high-voltage output) is provided to the high-voltage power supply via terminal 900. The V_{ref} signal is supplied to the positive input of comparator 910, via resistors 902 and 906 and capacitor 904, which together form a filter to eliminate voltage spikes on the input.

Comparator 910 controls the high-voltage charging circuitry to maintain a constant charge on the energy storage capacitors and receives on its negative input 912 a voltage sample signal which is related to the high-voltage output in the following manner. The high-voltage output on terminal 950 is provided to a voltage follower circuit via resistor 940. Resistor 940 is a voltage sampling resistor which typically has a large impedance (on the order of 15-20 megohms) to reduce the high-voltage output developed by the power supply to a manageable level. The high-voltage sample signal is provided to a filter consisting of resistors 932 and 936 and capacitor 934. The output of the filter is, in turn, applied to a differentiating voltage follower which is comprised of operational amplifier 920, resistors 916, 922 and 928 and diodes 924 and 926. A varistor 930 is connected across the input to the voltage follower to prevent voltage spikes from damaging the circuitry.

The output of the voltage follower, which is representative of the high-voltage output of the power supply, is provided to the negative input of comparator 910. The output of comparator 910, on lead 915, is, in turn, provided to an oscillator circuit, 970. Oscillator circuit 970 is enabled when a "high" signal appears on lead 915. Thus, when the voltage reference V_{ref} has a greater magnitude than the voltage sample signal, oscillator 970 is enabled. Oscillator 970, in turn, drives an SCR switching bridge 960 in a conventional manner. Switching bridge 960, in turn, drives the primary winding of transformer 954 which is a high-voltage step-up transformer. The secondary winding of transformer 954 develops a high-voltage output which is rectified by a conventional diode bridge 952 and applied to the high-voltage output terminal 950.

In operation, oscillator 970 operates to charge the energy storage capacitor (not shown) until the voltage sample signal developed by voltage follower 920 equals the voltage reference signal (V_{ref}) applied to terminal 900. At this point, the signal on lead 915 becomes "low" and oscillator 970 is disabled. If the voltage on the energy storage capacitor drops before the flashlamp is fired, the output sample voltage will decrease in proportion to the decrease in the high voltage output. This decrease will cause its magnitude to be below the voltage reference signal V_{ref} and comparator 910 will again be enabled to produce a "high" signal output on lead 915 which, in turn, will start oscillator 970. Accordingly, oscillator will begin recharging the energy storage capacitor.

Oscillator 970 also can be controlled means of the TRIGGER signal appearing on input 990. This TRIGGER signal is the same TRIGGER signal which is used to trigger the dump switch and fire the flashlamp, as previously described. The TRIGGER signal is used to disable oscillator 970 for a short time period after the flashlamp has been triggered so that the oscillator will not attempt to charge the energy storage capacitor while the flashlamp is being fired.

In particular, a "high" TRIGGER signal applied to terminal 990 is provided to the base of transistor 982, via a voltage divider consisting of resistors 984 and 986. The "high" signal turns on transistor 982 which, thereupon discharges capacitor 976. In addition, turned-on transistor 982 grounds lead 972, via diode 974. The "low" signal on lead 972 inhibits oscillator 970 and prevents charging of the energy storage capacitor. At the termination of the TRIGGER signal, the signal on terminal 990 becomes "low" which, in turn, turns off transistor 982. However, after transistor 982 turns off, lead 972 is held "low" by discharged capacitor 976. Capacitor 976 charges via resistor 980 and voltage source 978 and, after predetermined interval, lead 972 becomes "high" and oscillator 970 is re-enabled.

Utilizing the above apparatus a precisely-controlled sequence of pulses can be applied to any workpiece by appropriately building data files. In particular, a predetermined sequence of pulses having different peak energy, pulse width and pulse shape can be generated which sequence is

optimal for drilling a particular type of material. This ability to produce such a pulse sequence has enabled the discovery of certain general rules for drilling materials which rules were previously unnoticed because prior art systems could not consistently generate pulses with the same characteristics.

In accordance with the invention, in contrast with prior art methods which generally drilled a hole with a single laser shot or a small number or similar pulses, it has been found that a cleaner, better-defined hole can be produced by initially drilling a very small pilot hole and then reaming the hole using the laser to a final diameter. Therefore, in most materials a drilling pulse sequence divides into a number of defined phases. These consist of the following:

1. Entry with small diameter pulse
2. Middle section drilled with small diameter pulses
3. Exit with small diameter pulse
4. Widening to required diameter
5. Final reaming

When such a sequence is used in drilling, the resulting hole possesses virtually no recast layer on its inside wall. Apparently, this effect is due to the laser beam spatial power distribution. More specifically, when a hole is drilled with a single shot, a recast layer develops because melted material from the sides and bottom of the hole is

splattered on the sides of the hole by the shock wave which accompanies the arrival of the laser beam. When a small pilot hole is drilled and then reamed to the final diameter, the melted material is effectively vaporized and does not deposit on the sides of the hole. This vaporization takes place because of uneven power distribution in the laser beam. At higher power levels, the center of the beam has much higher power than the outer edges of the beam. Consequently, when such a beam is used to ream an existing hole, the edges of the beam melt the material on the sides of the hole. However, instead of being splattered against the sides of the hole, the melted material is ejected into the "hot" center of the beam where it is vaporized and carried out of the hole as vapor.

Each of the above phases can be drilled with a pulse sequence or group of a predetermined number of pulses which are identical in peak energy, pulse width, and pulse shape. However, between pulse groups the pulse characteristics must be changed.

In particular, in order to use such a sequence, some method must be devised to quickly change the diameter of the laser beam at the workpiece. Although prior art systems were available which could change the focal length of the optical path of the laser beam, these systems were impractical because they used mechanical means to refocus the optical system. If the drilling required more than a few laser pulses, the time required to mechanically refocus the system made drilling on a production scale impossible. However, in accordance

with the invention, the size of the spot at the workpiece can be controlled by controlling the flashlamp voltage and taking advantage of the thermal lensing effect which occurs. Thus, the laser beam spot size can be quickly and easily changed.

In addition, in accordance with the invention, in drilling various materials, especially those with a number of layers, it has been discovered that it is often advantageous to reduce the peak power of the pulses by reducing the flashlamp voltage in the entry phase as the laser beam initially enters the material. Such a procedure often helps to prevent delamination of the layers. For example, in the case of printed circuit boards the above procedure prevents delamination of the outer metallic layers. In order to provide reasonable drilling speed the peak power of the pulses is increased as the drilling progresses in the middle phase through the insulating layers and the pulses are again reduced in peak energy in the exit phase as the laser beam reaches the opposite side of the printed circuit board on which there is another metallic layer.

In order to determine the exact sequence used for drilling particular material, a test sequence can be programmed into the computer and then fired through the system and the results examined using the television monitor.

Two examples are given below for drilling two different types of material. One material is a copper-laminate board consisting of an insulating material with metallic layers on both sides. The

other material is a fourteen layer copper-laminate board. An illustrative sequence of pulses with associated flashlamp voltages is described for each example.

EXAMPLE 1

The workpiece material of this example is an FR-4 printed circuit board copper-laminate material. This material consists of fiberglass/epoxy resin insulating material covered on both sides with one-ounce copper foil. Overall thickness of the material is .010 inches, hole size to be drilled was .006 inches in diameter.

The greatest problem in drilling this thin laminate material was delamination of the metal layers on entrance and exit of the laser beam. It was possible to drill satisfactory circular holes with one laser pulse but the entrance and exit of the holes was badly marred. To avoid this distortion, the entry phase pulse group sequence generated by the computer controlled laser used very low-power pulses. The exit phase of the hole also had to be drilled with a low-power pulse sequence, again to prevent delamination. The middle phase of the hole could be drilled with a pulse group sequence with relatively high peak power to reduce drilling time as much as possible.

The material was drilled with a ruby laser constructed and controlled in accordance with the invention. The energy storage capacitors were 375 microfarads and a flashlamp pulse length of 400

microseconds was used. The laser threshold was approximately 970 volts and a pulse length of 400 microseconds was used. The following pulse group sequence was used (in this sequence each pulse is represented by a number which is the voltage applied to the flashlamp to generate the pulse):

<u>Pulse Grp</u> <u>Flashlamp Vlts</u>
<u>Pulses per grp.</u> <u>Drilling Phase</u>

1. 980
8 Ent, Mdl, Exit
2. 1000
3---------)
3. 1020
2)
4. 1050
2)
5. 1070
2)
6. 1090
2)Widening
7. 1100
2)
8. 1130
2)
9. 1150
2)
10. 1180
2---------)
11. 1200
2 Final Ream

The entry pulse sequence creates a small hole about .0005 - .001 inches in diameter. After this hole has been drilled through the work piece, the hole was widened using pulses with increasing power levels up to 1,200 volts for the final reaming pulses. As mentioned above, generally each pulse group will accomplish a particular objective, but because the test material is so thin in the example, the entry, middle and exit pulse groups are accomplished in pulse group one. Pulse groups 2-10 are used to widen the hole to proper diameter. Pulse group 11 is used for the final reaming. In accordance with the invention, it was found that if a small hole was initially drilled through the material, the application of successive pulses with higher peak power did not delaminate the surface and the hole could successfully be reamed to the proper final diameter.

EXAMPLE 2

In this example the workpiece material was FR-4 epoxy/fiberglass dielectric printed circuit board laminate consisting of fourteen alternating dielectric and metallic layers. One-ounce copper foil was used on all metallic layers as shown in Figure 10. In such thick material the different phases of drilling the hole become more pronounced as definite groupings. Entry piercing of the top layer of the copper was achieved in two to three low-power pulses. In particular, with a laser

threshold of 970 volts it was found that 2-3 three 980 volt pulses drilled through the top metallic layer and well into the first dielectric layer beneath.

Drilling of the middle portion of the hole in the case of a thick multilayer material becomes complicated. To obtain reasonable speed in drilling, power must gradually be increased as the hole progresses; otherwise it would take hundreds of pulses to reach the exit. Power must then be decreased at the exit of the laser beam from the material to prevent delamination. However, at all times the power must be kept well below the power level used for the final reaming cycle to avoid excessive cutting-back of the dielectric layers in the intermediate levels.

A successful pulse sequence for drilling the test material is as follows:

Pulse Grp	Pulses per grp.	Flashlamp Vlts	Drilling Phase
1.	5	980	Entry
2.	2----------	1020	)
3.	2	1030	)
4.	2	1040	)
5.	2	1050	)

6. 1060
2)Middle
7. 1070
2)
8. 1100
5)
9. 1150
8---------)
10. 1050
20 Exit
11. 1250
2---------)
12. 1280
2)
13. 1300
2)Widening
14. 1320
2)
15. 1350
5---------)
16. 1400
5 Final Ream

The exit portion of the pulse sequence is one group of twenty pulses. It is very important that the pulse that pierces the dielectric just before the last layer of copper as well as the last copper layer be at a low energy (in this example the last pulse is shot at 1050 flashlamp volts with a laser threshold of 970 volts). If the last pulse is not of low energy delamination of the last copper layer will begin to occur. At the final depth of the

hole, drilling through the last two layers of dielectric and copper, respectively, takes about 6-8 laser pulses. The remaining 12-14 pulses in the exit phase group provide some leeway in case the drilling program proceeded a little faster or a little slower than expected. Ideally, the last copper layer should be pierced by pulse numbers 12-14 of the exit phase pulse group. If the last layer is not pierced in the exit phase pulse group, but is pierced instead in either of the higher power pulse groups occuring before or after the exit phase group, delamination of the final metallic layer can occur.

Although any data handling and file manipulation computer software routine can be used to assemble the proper data files, the following program printout is an example of such a routine written in MICROSOFT Basic for the Apple II+ personal computer system. An explanation of the respective program commands can be found in the Applesoft Programmers Manual and in the Apple II+ Reference Manual.

See Appendix 1

Although only one embodiment of the invention has been shown in detail, obvious modifications of the invention will become immediately apparent to those skilled in the art. For example, lasers other than a ruby laser can be used with the inventive

system; the system can be used with neodynium:Yag lasers and CO_2 lasers as well as ruby lasers. Other possible laser materials are emerald and Alexandrite. These and other more obvious modifications are intended to be covered by the following claims.

Claims

1. A method of drilling a hole through a workpiece material by means of apparatus having a radiant energy source, a programmable controller and a memory, said method comprising the steps of:
   A. irradiating said material with a beam of radiant energy from said source, said beam being capable of locally heating said material to at least its melting temperature;
   B. controlling said radiant energy source by means of a command to said programmable controller to produce a temporal pulse of radiant energy at said workpiece with a predetermined spot size, peak pulse energy and pulse shape;
   C. determining a set of programming commands which result in a sequence of pulses having selected spot sizes, peak pulse energies and pulse shapes, which pulse sequence produces an acceptable hole in said material;
   D. storing said program command set in said memory; and
   E. extracting said programming commands in order from said memory and applying said commands to said controller to produce a pulsed drilling sequence for drilling said material.

2. A method in accordance with Claim 1 further comprising the steps of:

F. applying a first set of programming commands to said controller to cause said radiant energy source to generate a sequence of small spot size, low peak power pulses to said workpiece so that a small hole is drilled through said workpiece; and

G. applying a second set of programming commands to said controller to cause said radiant energy source to generate a sequence of high peak power pulses with gradually increasing spot size to said workpiece so that the hole drilled through said workpiece in accordance with step F is widened to a final width.

3. A method in accordance with Claim 1 wherein said drilling apparatus further includes a programmable power supply and step B further comprises the steps of:

B'. applying said command to a programmable power supply to cause said power supply to produce a predetermined voltage; and

B". applying the voltage developed by said power supply to said radiant energy source to cause the generation of said pulse.

4. A method of drilling a hole through a workpiece laminate composed of a plurality of layers of different materials with drilling apparatus comprised of a radiant energy source, said method comprising the steps of:

A. irradiating said laminate with a beam of radiant energy from said source, which beam is capable of heating each of said materials to at least its melting temperature;

B. controlling said source to form said beam into a temporal sequence of pulses of said energy, said pulses having variable spot size at said laminate, varying peak pulse energy and varying pulse shape; and

C. controlling said radiant energy source so that the pulses at the beginning and end of said sequence have substantially lower peak pulse energy than the pulses in the middle of said sequence so as to pierce the outer layers of said laminate sufficiently slowly to avoid delamination, and to drill the intermediate layers of said laminate at increased speed.

5. A method according to Claim 4 further comprising the steps of:

D. irradiating said workpiece with a further sequence of said pulses, each of said pulses in said second sequence having increased peak pulse energy for widening said hole drilled in accordance with step C.

6. A method according to Claim 5 in which step C further comprises the steps of:

C'. gradually increasing the peak pulse power of each pulse in said sequence as the

drilling progresses toward the middle of said laminate; and

C'. gradually decreasing the peak pulse power of each pulse in said sequence as the drilling reaches the exit of the hole.

7. A method of drilling a hole through a workpiece material by means of apparatus having a laser, a programmable power supply, and a computer, including a central processing unit and a memory, said method comprising the steps of:

A. irradiating said material with a beam of radiant energy from said laser, said beam being capable of locally heating said material to at least its melting temperature;

B. generating a voltage control command with said computer;

C. applying said voltage control command to said programmable power supply to cause it to produce a predetermined output voltage;

D. applying said output voltage to said laser to cause said laser to produce a temporal pulse of radiant energy at said workpiece with a predetermined spot size, peak pulse energy and pulse shape;

E. determining a set of voltage control commands which result in a sequence of pulses having selected spot sizes, peak pulse energies and pulse shapes, which pulse sequence produces an acceptable hole in said material;

F. storing said voltage control command set in said memory; and

G. extracting said programming commands in order from said memory and applying said commands to said power supply to produce a pulsed drilling sequence for drilling said material.

8. A method in accordance with Claim 7 further comprising the steps of:

H. applying a first set of voltage control commands to said power supply to cause said laser to generate a sequence of small spot size, low peak power pulses at said workpiece so that a small hole is drilled through said workpiece; and

I. applying a second set of voltage control commands to said power supply to cause said laser to generate a sequence of high peak power pulses with gradually increasing spot size at said workpiece so that the hole drilled through said workpiece in accordance with step H is widened to a final width.

9. A method of drilling a hole through a workpiece material in accordance with Claim 7 wherein said laser comprises a laser crystal and a flashlamp for exciting said laser crystal and step D further comprises the steps of:

D'. applying said output voltage to said flashlamp to cause excitation of said laser crystal.

10. A method of drilling a hole through a workpiece material by means of apparatus having a laser crystal and a flashlamp for exciting said laser crystal, a programmable power supply, and a computer, including a central processing unit and a memory, said method comprising the steps of:

A. generating a beam of radiant energy from said laser crystal;

B. focussing said beam to a spot;

C. passing said beam through a pinhole to eliminate marginal rays;

D. focussing the energy emerging from said pinhole on said workpiece material, said beam being capable of locally heating said material to at least its melting temperature;

E. generating a voltage control command with said computer;

F. applying said voltage control command to said programmable power supply to cause it to produce a predetermined output voltage;

G. applying said output voltage to said flashlamp to cause said laser crystal to produce a temporal pulse of radiant energy at said workpiece with a predetermined spot size, peak pulse energy and pulse shape;

H. examining the workpiece to determine the depth and quality of the hole caused by said pulse;

I. storing a representation of said voltage control command in said memory;

J. repeating steps H and I to determine a set of voltage control commands which result in a sequence of pulses having selected spot sizes, peak pulse energies and pulse shapes, which pulse sequence produces an acceptable hole in said material; and

K. extracting said programming commands in order from said memory and applying said commands to said power supply to produce a pulsed drilling sequence for drilling said material.

11. A method in accordance with Claim 10 further comprising the steps of:

L. applying a first set of voltage control commands to said power supply to cause said laser crystal to generate a sequence of small spot size, low peak power pulses at said workpiece so that a small hole is drilled through said workpiece; and

M. applying a second set of voltage control commands to said power supply to cause said laser crystal to generate a sequence of high peak power pulses with gradually increasing spot size at said workpiece so that the hole drilled through said workpiece in accordance with step L is widened to a final width.

12. Apparatus for drilling a hole through a workpiece material, said apparatus comprising,

a radiant energy source controllable to irradiate said material with a beam of radiant energy, said beam being capable of locally heating said material to at least its melting temperature,

a control unit responsive to a command for controlling said radiant energy source to produce a temporal pulse of radiant energy at said workpiece with a predetermined spot size, peak pulse energy and pulse shape;

programmable means for generating a set of commands which control said radiant energy source to generate a sequence of pulses having selected spot sizes, peak pulse energies and pulse shapes, which pulse sequence produces an acceptable hole in said material;

a memory for storing said set of programming commands,

means for extracting said programming commands in order from said memory, and

means responsive to said extracted commands for applying said commands to said control unit to produce a pulsed drilling sequence for drilling said material.

13. Apparatus in accordance with Claim 12 wherein said control unit further comprises a programmable power supply responsive to said command for producing a predetermined output voltage, and means for applying said output

voltage developed by said power supply to said radiant energy source to cause the generation of said pulse.

14. Apparatus for drilling a hole through a workpiece material, said apparatus comprising,

a laser controllable to irradiate said material with a beam of radiant energy, said beam being capable of locally heating said material to at least its melting temperature,

a computer, including a central processing unit and a memory, said computer being programmable to generate a voltage control command,

a programmable power supply,

means responsive to said voltage control command for controlling said programmable power supply to produce a predetermined output voltage, means for applying said output voltage to said laser to cause said laser to produce a temporal pulse of radiant energy at said workpiece with a predetermined spot size, peak pulse energy and pulse shape,

means for storing a set of voltage control commands in said memory, which set of voltage control commands results in a sequence of pulses having selected spot sizes, peak pulse energies and pulse shapes, which pulse sequence produces an acceptable hole in said material,

means for extracting said voltage control commands in order from said memory, and

means responsive to said extracted voltage control commands for applying said commands to said power supply to produce a pulsed drilling sequence for drilling said material.

15. Apparatus for drilling a hole through a workpiece material in accordance with Claim 14 wherein said laser comprises a laser crystal and a flashlamp for exciting said laser crystal and said means for applying said output voltage to said laser comprises means for applying said output voltage to said flashlamp to cause excitation of said laser crystal.

16. Apparatus for drilling a hole through a workpiece material comprising,

a laser crystal for generating a beam of radiant energy, said beam being capable of locally heating said material to at least its melting temperature;

a first convex lens for focussing said beam to a spot;

a pinhole located at the focal point of said first lens for eliminating marginal rays;

a second convex lens for focussing the energy emerging from said pinhole on said workpiece material,

a flashlamp located in the vicinity of said crystal for exciting said laser crystal,

a programmable power supply connected to said flashlamp for energizing said lamp,

a computer, including a central processing unit and a memory for generating a plurality of voltage control commands,

means for applying said voltage control commands to said programmable power supply to cause it to produce a predetermined output voltage in turn to cause said laser crystal to produce a sequence of temporal pulses of radiant energy at said workpiece each of said pulses having a predetermined spot size, peak pulse energy and pulse shape,

means for examining the workpiece to determine the depth and quality of the hole caused by said sequence of pulses,

means for storing a representation of said voltage control commands in said memory,

means for extracting said programming commands in order from said memory, and

means responsive to said extracted commands for applying said commands to said power supply to produce a pulsed drilling sequence for drilling said material.

17. Apparatus in accordance with Claim 16 wherein said laser crystal is a ruby laser crystal.

18. Apparatus in accordance with Claim 16 further comprising cooling means for cooling said laser crystal and said flashlamp to a predetermined temperature to stabilize the effective focal length of said system so that the spot size of

the spot of radiant energy focussed on said workpiece is substantially determined by the physical configuration of said laser crystal.

19. Apparatus in accordance with Claim 16 wherein said power supply is a simmer power supply.

20. Apparatus in accordance with Claim 16 wherein said power supply further comprises energy storage capacitors connected to said supply for storing a charge to fire said flashlamp and means for preventing voltage drift during the time between charging of the energy storage capacitors and firing of the flashlamp.

21. Apparatus for drilling a hole through a workpiece material comprising,

a laser crystal for generating a beam of radiant energy, said beam being capable of locally heating said material to at least its melting temperature;

a flashlamp located in the vicinity of said crystal for exciting said laser crystal,

a first convex lens located at a fixed distance from said laser crystal for focussing said beam to a spot;

a pinhole located at the focal point of said first lens for eliminating marginal rays;

a second convex lens located a fixed distance from said pinhole for focussing the energy emerging from said pinhole on said workpiece material, said workpiece material being located at a fixed distance from said

second lens so that the effective spot size of the radiant energy on said workpiece is determined by the lensing characteristics of said laser crystal, and

cooling means for cooling said laser crystal and said flashlamp to a predetermined temperature to stabilize the effective focal length of said system so that the spot size of the spot of radiant energy focussed on said workpiece is substantially determined by the energy provided to said crystal by said flashlamp.

22. Apparatus in accordance with Claim 21 wherein said laser crystal is a ruby laser crystal.

23. A method of drilling a hole through a workpiece with drilling apparatus comprised of an optical system, including a radiant energy source which is capable of thermal lensing, said method comprising the steps of:

A. irradiating said workpiece with a beam of radiant energy pulses from said source, which beam is capable of heating said workpiece to at least its melting temperature;

B. controlling said pulses so as to irradiate said workpiece with a first sequence of pulses of said radiant energy for piercing said workpiece, said pulses in said first sequence having minimal peak pulse power for forming a small diameter hole through said workpiece; and

C. controlling said pulses so as to irradiate said hole in said workpiece with a second sequence of said pulses, each of said pulses in said second sequence having increased peak pulse energy for changing the focus of said optical system and thereby widening said hole.

24. A method according to Claim 23 wherein said first sequence further comprises the steps of:

D. gradually increasing the peak pulse power of each pulse in said first sequence as the drilling progresses toward the middle of said workpiece; and

E. gradually decreasing the peak pulse power of each pulse in said first sequence as the drilling reaches the exit of the hole.

25. Apparatus for drilling a hole through a workpiece comprising an optical system, including a radiant energy source which is capable of thermal lensing, said apparatus comprising,

means for irradiating said workpiece with a beam of radiant energy pulses from said source, said beam being focussed on a region of said workpiece for heating said region to at least the melting temperature of said workpiece,

means for controlling said pulses to provide a first sequence of pulses having minimal peak power for forming a small-diameter hole through said workpiece, and

means for controlling said pulses to provide a second sequence of pulses having increased peak pulse energy so that the focussing characteristics of said optical system are changed, whereby the hole is widened.

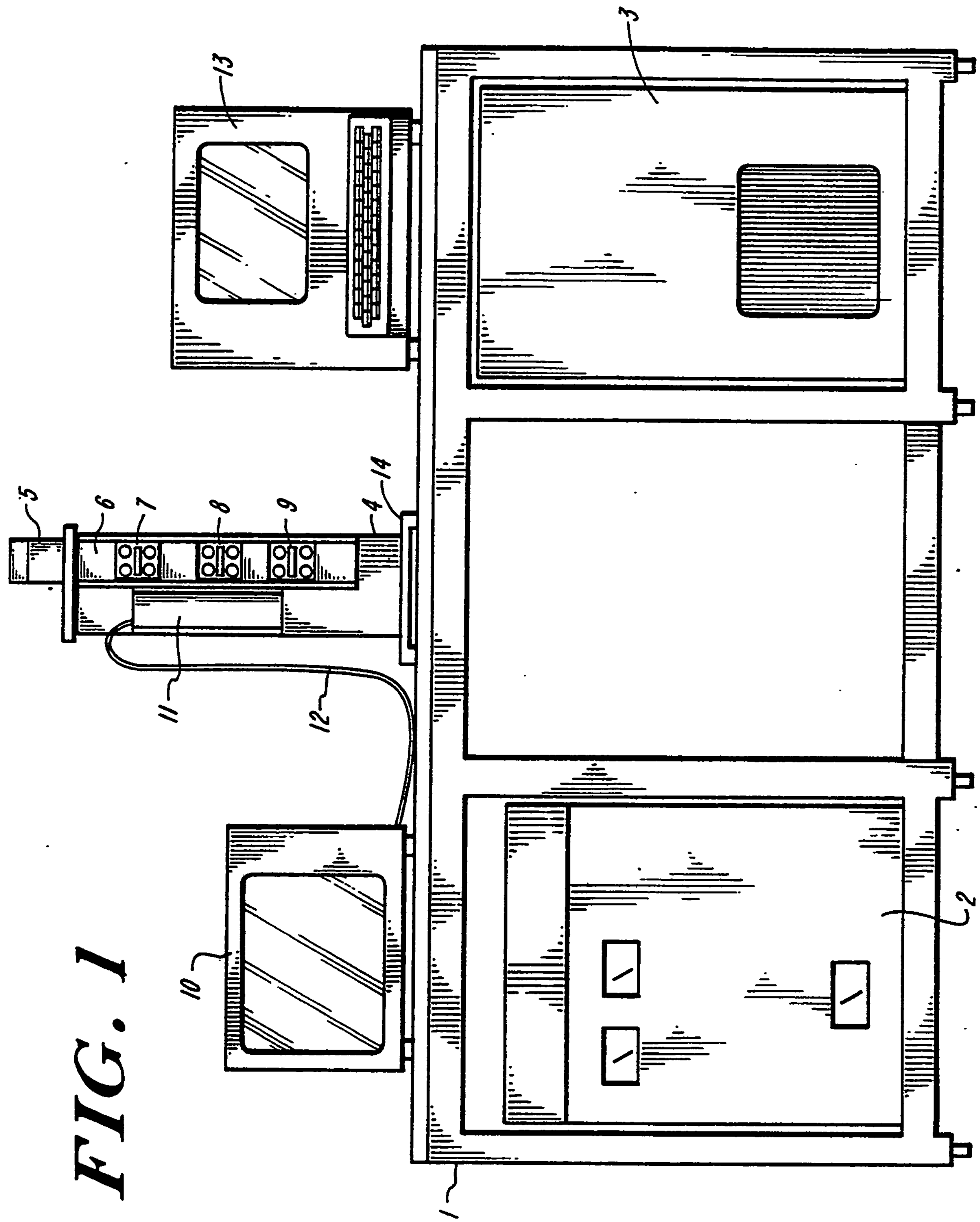

FIG. 1

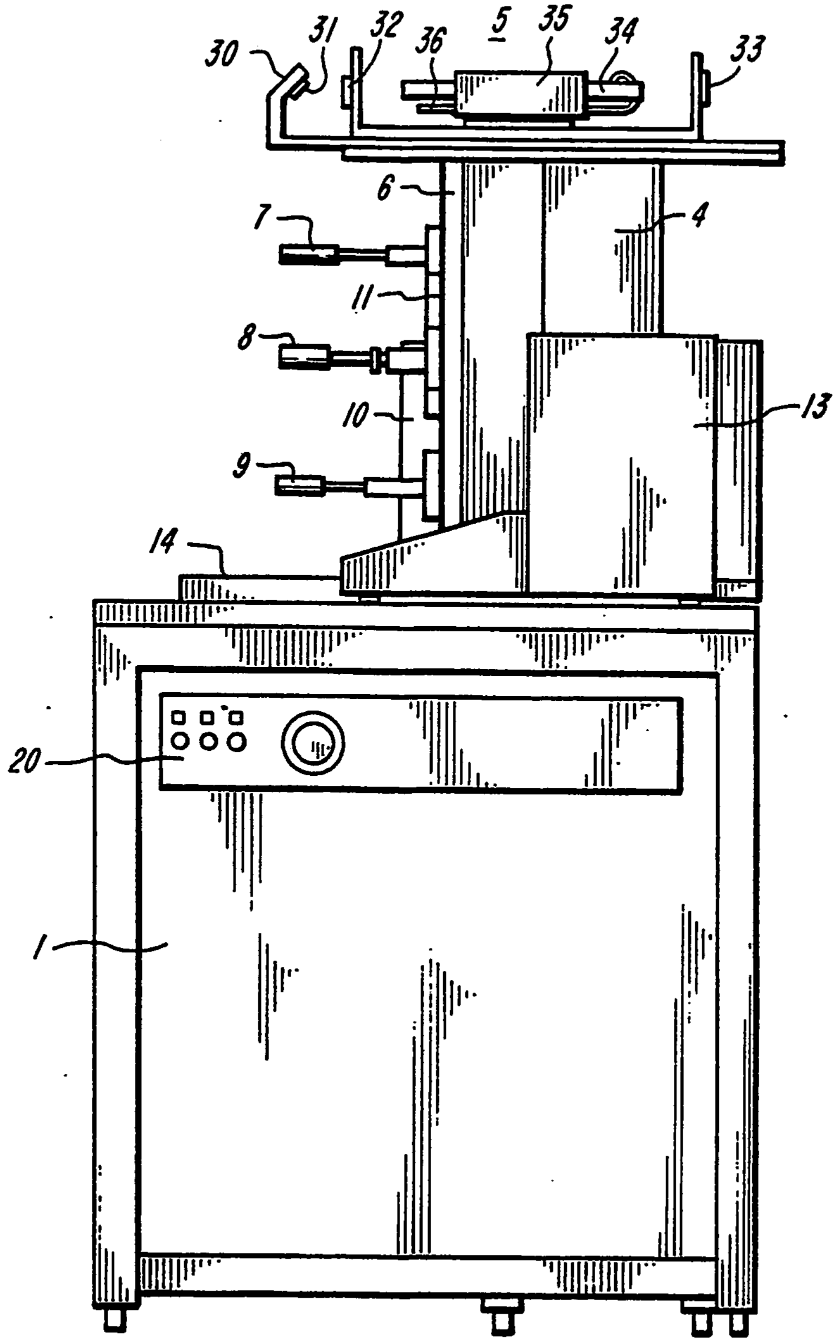

FIG. 2

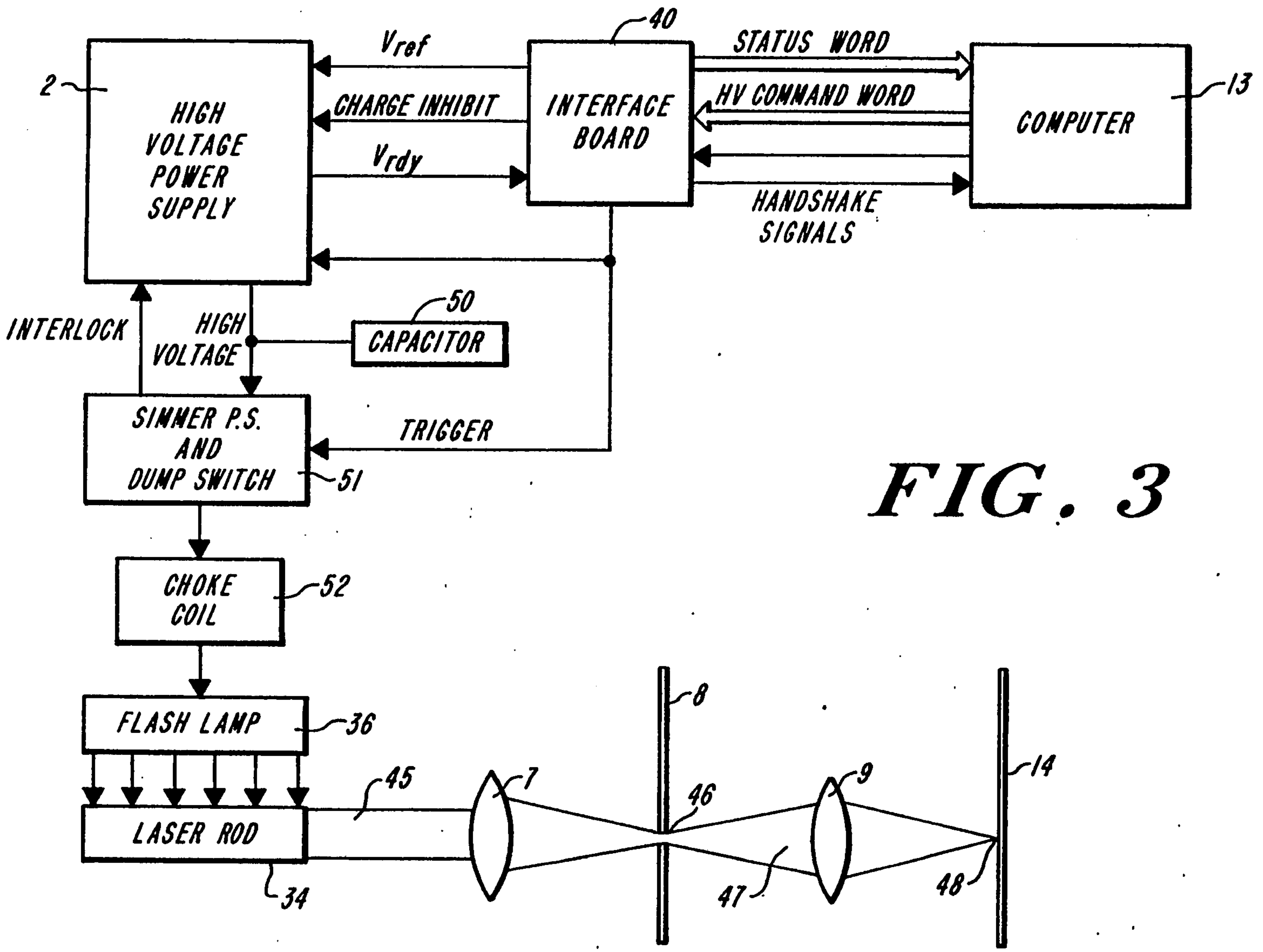
HIGH VOLTAGE POWER SUPPLY
2
Vref
CHARGE INHIBIT
Vrdy
INTERFACE BOARD
40
STATUS WORD
HV COMMAND WORD
HANDSHAKE SIGNALS
COMPUTER
13
INTERLOCK
HIGH VOLTAGE
CAPACITOR
50
TRIGGER
SIMMER P.S. AND DUMP SWITCH
51
CHOKE COIL
52
FLASH LAMP
36
LASER ROD
34
45
7
8
46
47
9
48
14

FIG. 3

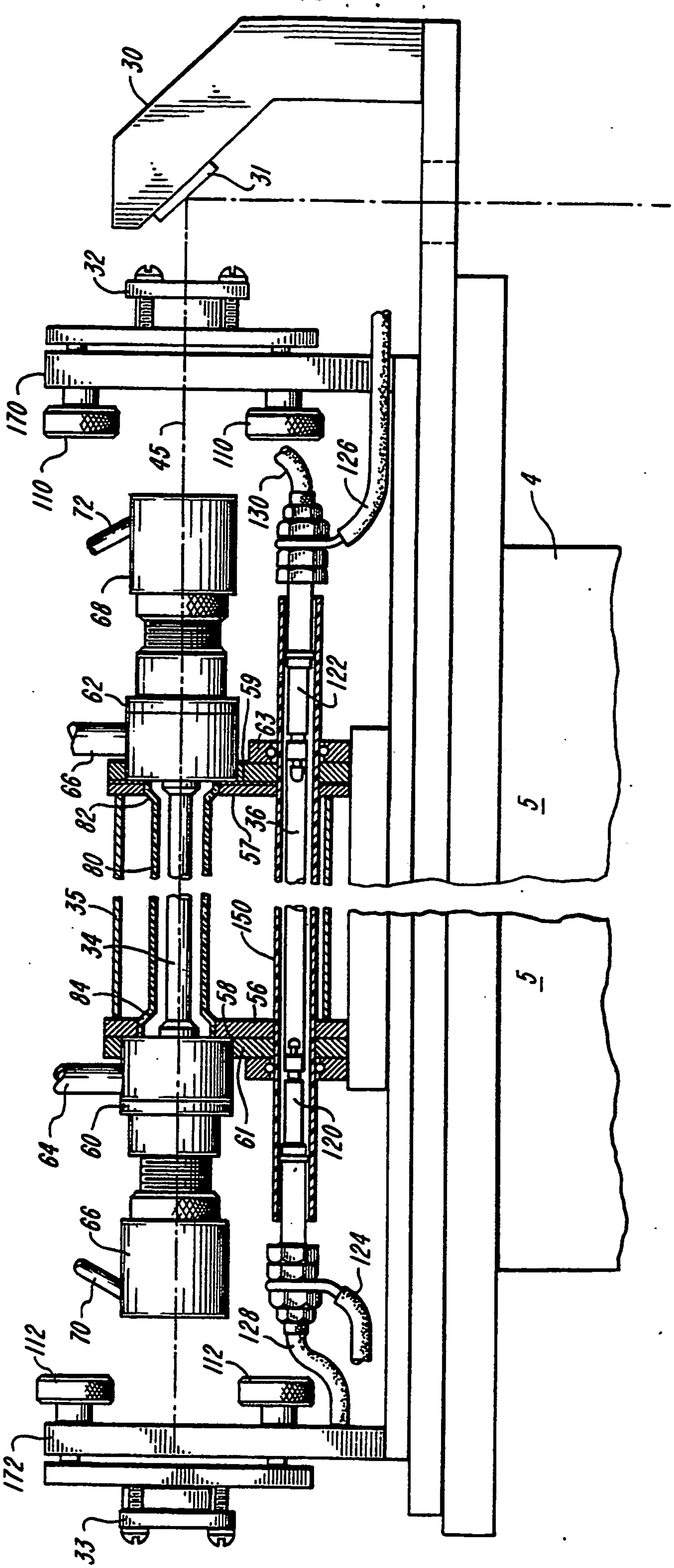
30
31
32
170
110
45
110
126
130
72
68
4
122
62
59
63
66
82
57
36
80
5
35
150
34
84
58
56
5
64
60
61
120
66
70
124
128
112
112
172
33

FIG. 4

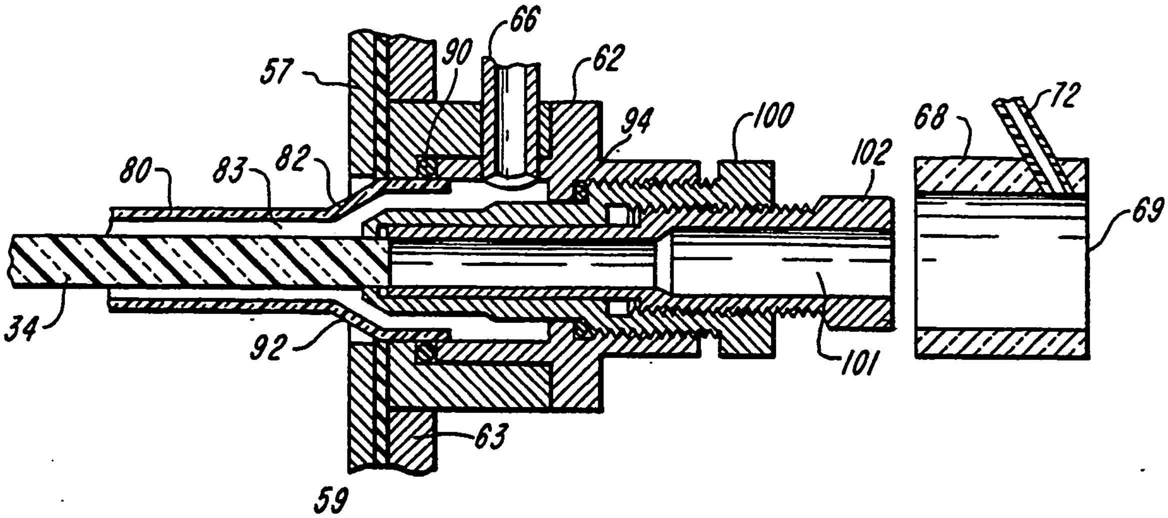

FIG. 5

	600	650	652	654
	TOTAL NUMBER OF GROUPS 601	TOTAL NUMBER OF SHOTS 656	LASER TYPES 658	660
GROUP 1	NUMBER OF SHOTS GRP #1 602	LASER TYPE GRP #1	RAW VOLTS GRP #1	BINARY CODED VOLTS GRP #1
GROUP 2	NUMBER OF SHOTS GRP #2	LASER TYPE GRP #2	RAW VOLTS GRP #2	BINARY CODED VOLTS GRP #2
	⋮	⋮	⋮	⋮
	620			
GROUP N-1	NUMBER OF SHOTS GRP #N-1 622	LASER TYPE GRP #N-1	RAW VOLTS GRP #N-1	BINARY CODED VOLTS GRP #N-1
GROUP N	NUMBER OF SHOTS GRP #N	LASER TYPE GRP #N	RAW VOLTS GRP #N	BINARY CODED VOLTS GRP #N

FIG. 6

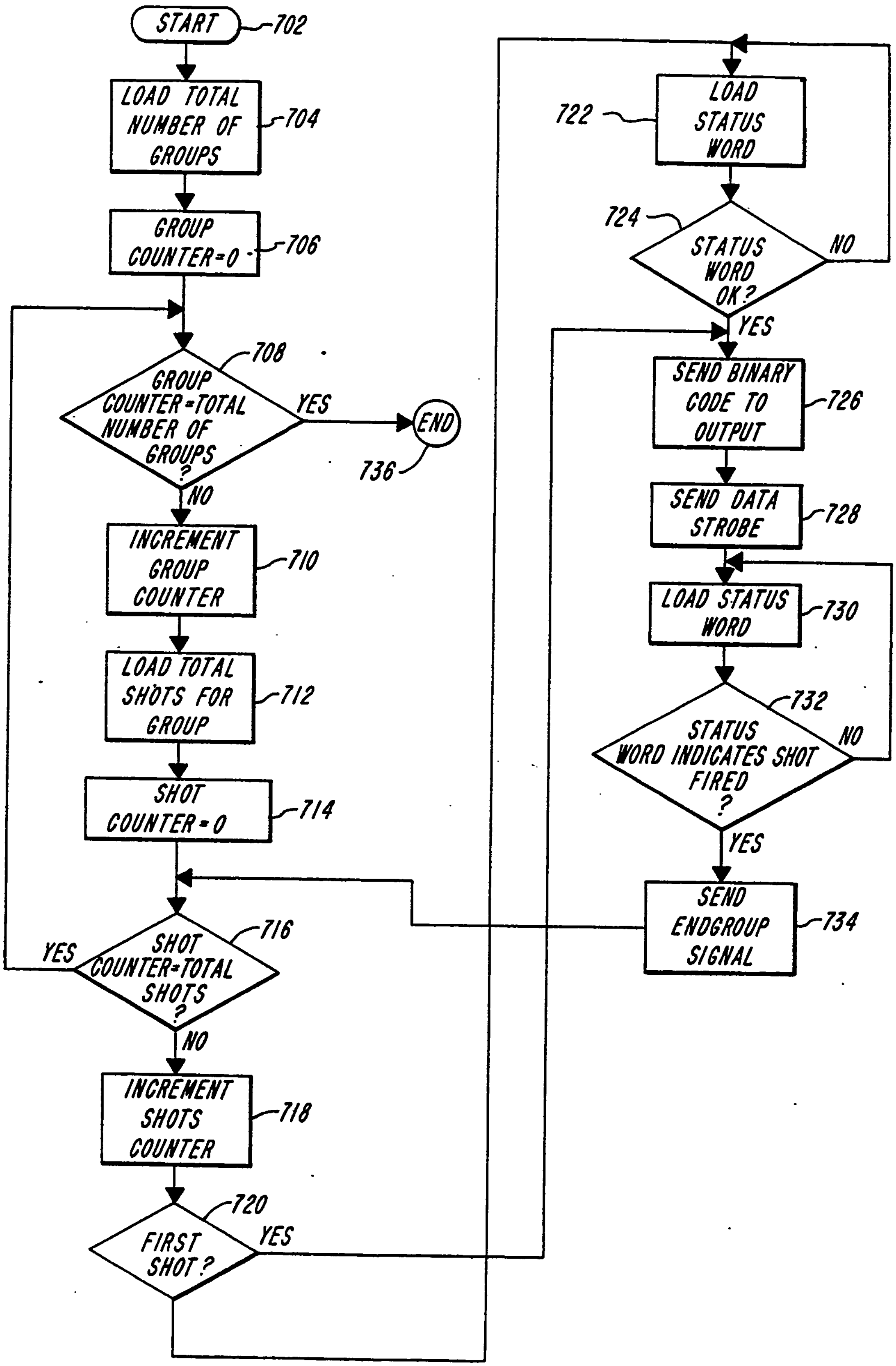
START
702
LOAD TOTAL NUMBER OF GROUPS
704
GROUP COUNTER=0
706
GROUP COUNTER=TOTAL NUMBER OF GROUPS ?
708
YES
END
736
NO
INCREMENT GROUP COUNTER
710
LOAD TOTAL SHOTS FOR GROUP
712
SHOT COUNTER=0
714
SHOT COUNTER=TOTAL SHOTS ?
716
YES
NO
INCREMENT SHOTS COUNTER
718
FIRST SHOT ?
720
YES
LOAD STATUS WORD
722
STATUS WORD OK?
724
NO
YES
SEND BINARY CODE TO OUTPUT
726
SEND DATA STROBE
728
LOAD STATUS WORD
730
STATUS WORD INDICATES SHOT FIRED ?
732
NO
YES
SEND ENDGROUP SIGNAL
734

FIG. 7

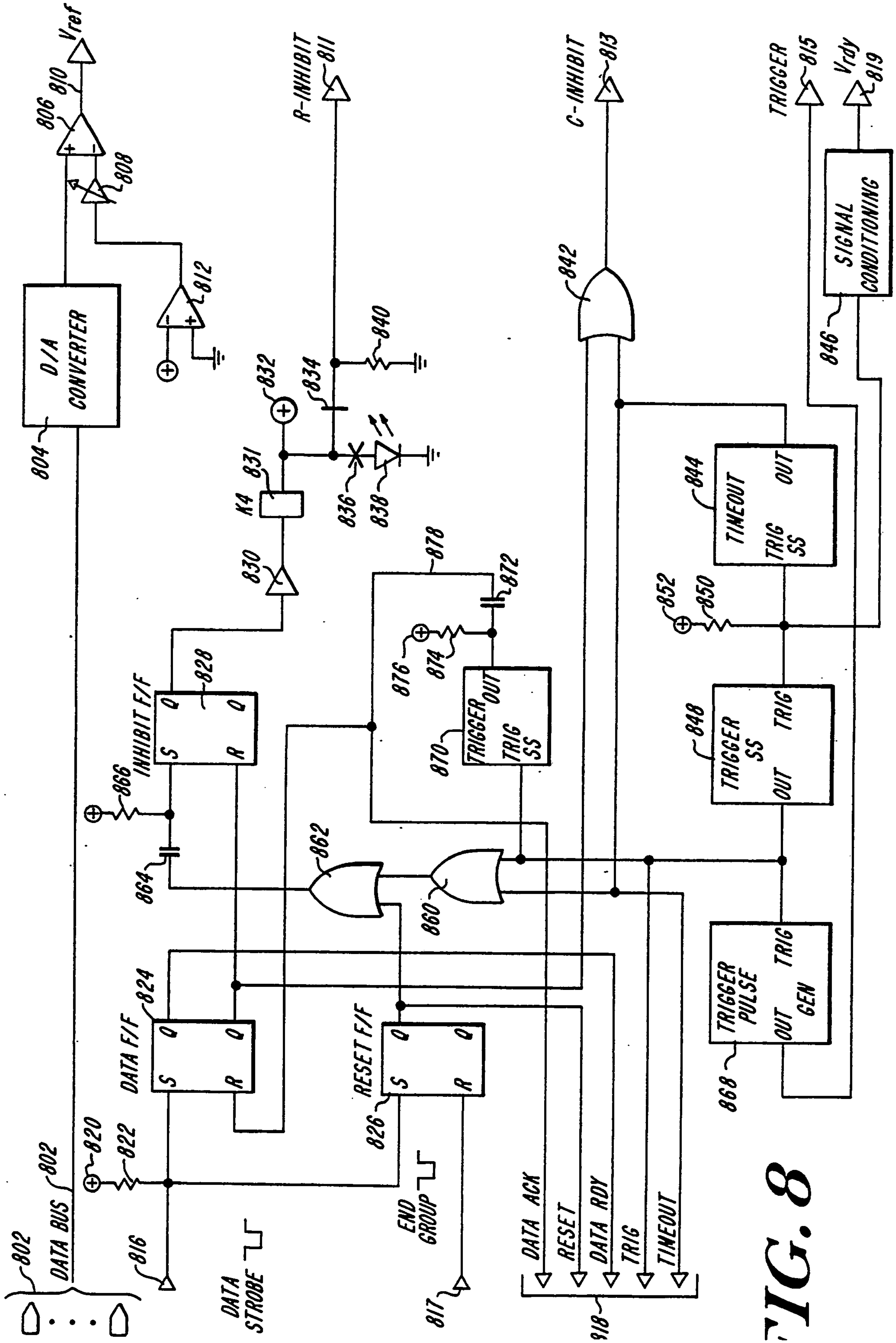
Vref
806
810
808
812
D/A CONVERTER
804
R-INHIBIT
811
832
834
840
K4
831
836
838
830
878
872
876
874
INHIBIT F/F
828
866
864
862
860
TRIGGER OUT
TRIG SS
870
DATA F/F
824
RESET F/F
826
820
822
802
DATA BUS
816
DATA STROBE
END GROUP
817
DATA ACK
RESET
DATA RDY
TRIG
TIMEOUT
818
C-INHIBIT
813
842
TRIGGER
815
Vrdy
819
SIGNAL CONDITIONING
846
TIMEOUT
TRIG SS
OUT
844
852
850
TRIGGER SS
OUT
TRIG
848
TRIGGER PULSE GEN
868

FIG.8

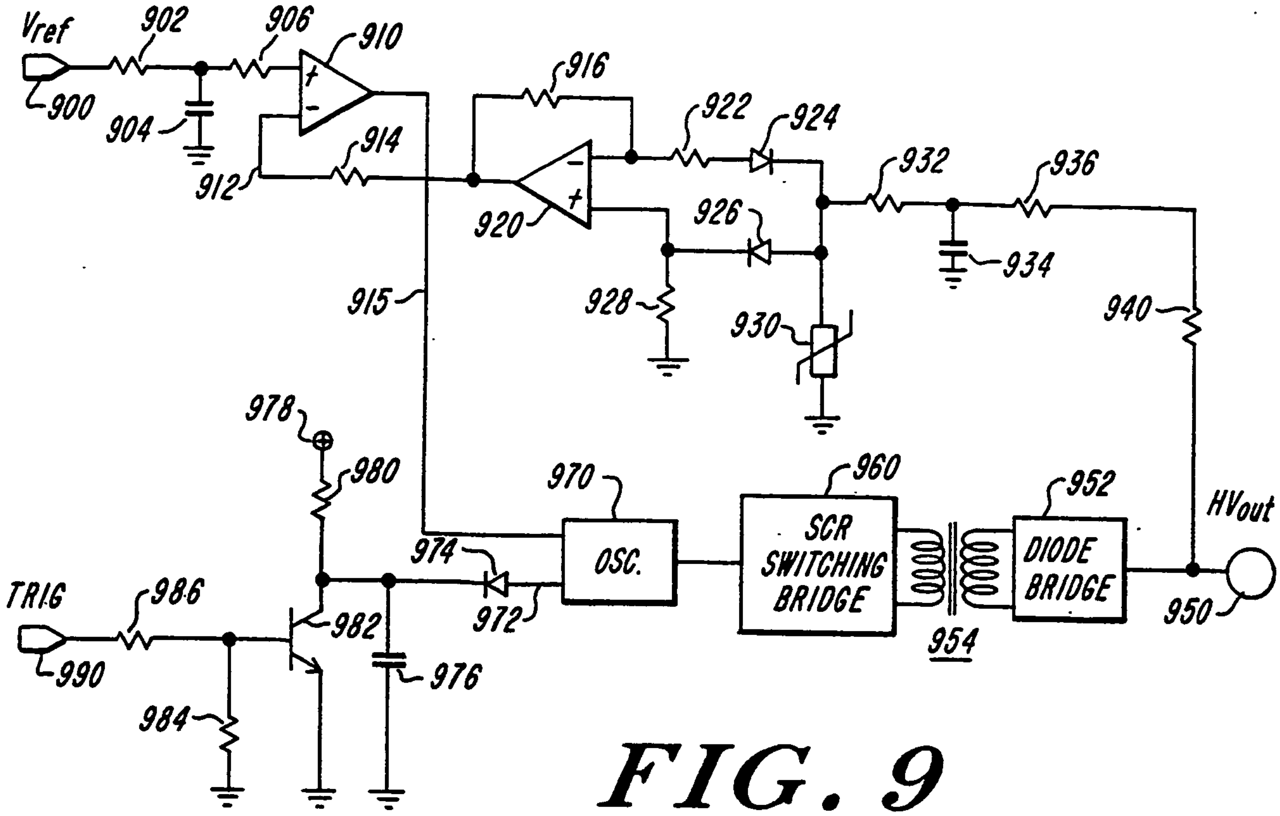

FIG. 9

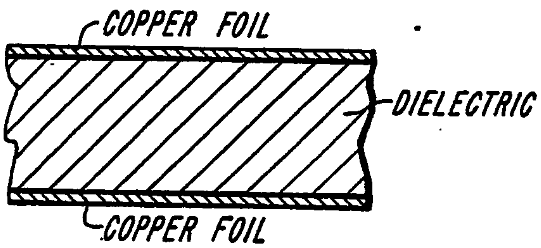

FIG. 10

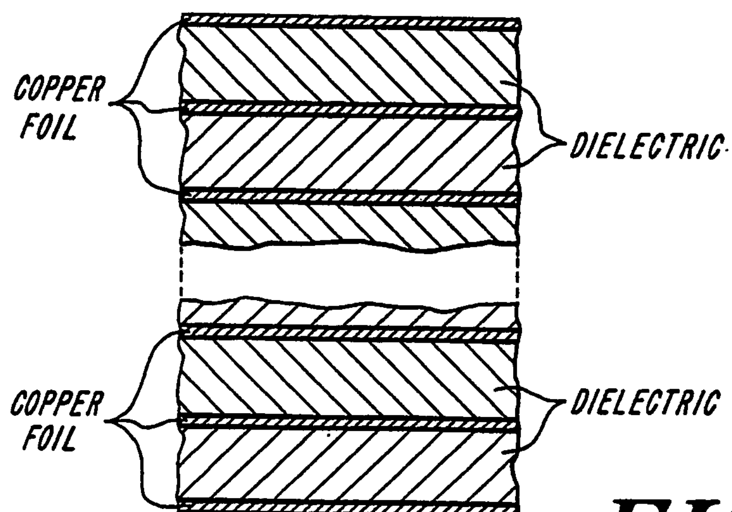

FIG. 11

INTERNATIONAL SEARCH REPORT

International Application No PCT/US 85/01928

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC^4: B 23 K 26/00; B 26 F 1/31

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
IPC^4	B 23 K; B 26 F

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category [*]	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	IBM Technical Disclosure Bulletin, vol. 24, no. 9, February 1982 (New York, US) H.E. Klauser: "Closed loop laser control system", pages 4691-4693, see the entire document	1,2
A		4,5,10,12,16 21,23-25
Y		3,7-9,14,15
	--	
X	US, A, 3806829 (D.K. DUSTON et al.) 23 April 1974 see column 1, lines 18-28; column 1, line 60 - column 2, line 39; column 3, line 6 - column 4, line 13; column 4, line 55 - column 5, line 23; column 6, line 15 - column 8, line 29; column 8, line 54 - column 11, line 33; column 13, line 66 - column 15, line 28; column 17, line 45 - column 18, line 49; column 31, lines 30-60; figures 1,2-5,6	12,13
Y		3,7-9,14,15
A	./.	1,2,10,16-23

* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
18th February 1986	26 MARS 1986
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	M. VAN MOL

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
		25
	--	
A	US, A, 4114018 (H. VON ALLMEN et al.) 12 September 1978 see abstract; column 2, line 49 - column 3, line 25; column 4, lines 25-31; column 5, line 63 - column 6, line 23; column 7, line 44 - column 8, line 31; column 8, line 49 - column 9, line 43; column 10, line 57 - column 11, line 42; figures 1-11	1,4-7,21,23-25
	--	
A	BE, A, 849646 (W.W. SALISBURY et al.) 20 June 1977 see page 1, line 18 - page 3, line 6; page 6, lines 2-8; page 6, line 34 - page 9, line 35; figures 1,4	1,2,4-8,23-25
	--	
P,X	EP, A1, 0129462 (SOCIETE NATIONALE D'ETUDE ET DE CONSTRUCTION DE MOTEURS D'AVION) 27 December 1984 see page 6, lines 8-23; page 7, line 25 - page 9, line 4; page 12, line 16 - page 19, line 8; figures 3,4	1,2,12
	--	
A	US, A, 3388461 (S.J. LINS) 18 June 1968 see column 6, line 18 - column 7, line 51	1,7,9,10,12,15-18,20-23

INTERNATIONAL APPLICATION NO. PCT/US 85/01928 (SA 11329)

This Annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 19/03/86

The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A- 3806829	23/04/74	None	
US-A- 4114018	12/09/78	None	
BE-A- 849646	20/06/77	None	
EP-A- 0129462	27/12/84	FR-A- 2547519 JP-A- 60012292	21/12/84 22/01/85
US-A- 3388461		None	